UNIVERSITY OF LONDON THESIS

Degree PhD Year 2005 Name of Author LI, C.

COPYRIGHT
This is a thesis accepted for a Higher Degree of the University of London. It is an unpublished typescript and the copyright is held by the author. All persons consulting the thesis must read and abide by the Copyright Declaration below.

COPYRIGHT DECLARATION
I recognise that the copyright of the above-described thesis rests with the author and that no quotation from it or information derived from it may be published without the prior written consent of the author.

LOANS
Theses may not be lent to individuals, but the Senate House Library may lend a copy to approved libraries within the United Kingdom, for consultation solely on the premises of those libraries. Application should be made to: Inter-Library Loans, Senate House Library, Senate House, Malet Street, London WC1E 7HU.

REPRODUCTION
University of London theses may not be reproduced without explicit written permission from the Senate House Library. Enquiries should be addressed to the Theses Section of the Library. Regulations concerning reproduction vary according to the date of acceptance of the thesis and are listed below as guidelines.

A. Before 1962. Permission granted only upon the prior written consent of the author. (The Senate House Library will provide addresses where possible).

B. 1962 - 1974. In many cases the author has agreed to permit copying upon completion of a Copyright Declaration.

C. 1975 - 1988. Most theses may be copied upon completion of a Copyright Declaration.

D. 1989 onwards. Most theses may be copied.

This thesis comes within category D.

☑ This copy has been deposited in the Library of UCL

☐ This copy has been deposited in the Senate House Library, Senate House, Malet Street, London WC1E 7HU.

Pedestrian Wayfinding using Mobile Devices:

an investigation of spatial information transactions and interaction

Chao Li

University College London

PhD

2005

UMI Number: U592286

Abstract

Wayfinding is a fundamental spatial activity that people experience in their daily lives. Human wayfinding is often assisted by external aids. Recent developments in mobile information and telecommunication technologies are stimulating demand for services that can deliver, to individuals on the move, location-specific information to assist wayfinding. Such services are known as Location-Based Services (LBS). This research aims to investigate the interaction and information transactions between individuals, urban environments and mobile technologies for individuals engaged in pedestrian wayfinding. A novel conceptual model is proposed which explicitly focuses on these interactions and transactions. One of the challenges is to objectively record the overt information transactions and behavioural responses when individuals use mobile technologies for wayfinding in urban settings. Therefore, in this research, an immersive virtual reality approach has been proposed and implemented for capturing data in real-time in a dynamic environment. This test environment integrates three main components: urban VR models that allow individuals to 'walk around' at street level, a mobile device as information source which simulates LBS applications, and software for recording participant actions and reactions within the test environment. Multi-source data were collected regarding movement tracking, information accessed through the mobile device and observations of participants' actions using a combination of automated and semi-automated methods. This has provided a rich data source detailing individual overt behaviour in space and time for pedestrian wayfinding tasks. Contrasting urban models were constructed having their own distinctive layouts and mix of architectures. A series of detailed empirical wayfinding experiments have been carried out using this controlled setting and research design. Detailed analyses, both quantitative and qualitative, are performed on the integrated data sets. One key focus has been on establishing patterns of spatial information usage preferences in terms of types of information, frequency of access, and time spent in consulting the information. A classification of spatial information usage groups has been developed. Characteristics of these groups in terms of their spatial abilities and information usage during wayfinding are explored. It has also been possible to confirm certain effects of urban layout on behaviour and has highlighted key spatial loci for information demand and decision making. An integrated picture of participant behaviour and spatial information preferences is thus constructed through the analyses.

Acknowledgements

I would like to sincerely thank:

- my supervisors Professor Paul Longley for his support and his critical review of the research

  Professor Michael Batty for his support and encouragement

- the ESRC for their support of this research through a studentship
- Ordnance Survey for the provision of map data
- Hewlett Packard Labs, Bristol for the donation of a Jornado 568 PDA
- all the participants in my experiments for their courage and fortitude

- my husband, parents and brother for their unwavering support and tolerance, without whom I may not have found my way to here!

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER ONE
Introduction

Wayfinding is a fundamental spatial activity that people experience in their daily lives. It can be described as purposive and motivated movement by an individual to a specific and distant destination that cannot be seen directly (Heft, 1983; Garling *et al.*, 1984; Blades 1991; Golledge, 1992). Wayfinding is also an interactive behaviour between people and their environments. The environment is a dynamic source of information used by people in their wayfinding decision-making processes. Lynch (1960), in his seminal work, suggests that during wayfinding "there is a consistent use and organization of definite sensory cues from the external environment". Furthermore, wayfinding is a form of spatial problem solving. Thus, during wayfinding activities, people undertake a sequential process of decision making in which the purpose is to match internal with external information as it is obtained (Stern and Portugali, 1999). There is a clear consensus, in wayfinding research, that differences exist between the environments that people perceive subjectively, and in the way people acquire, develop and use spatial information for their wayfinding activities (Golledge, 1999). Since wayfinding is purposive behaviour involving people and environments, another important aspect of wayfinding is the individual's spatial ability for carrying out such activities. Individual differences in spatial ability will have an effect upon spatial knowledge acquisition during wayfinding and hence the success of wayfinding activities. In general, the characteristics of people and the attributes of environments influence whether and how well wayfinding is achieved (Allen, 1999b). The acquisition of spatial knowledge and performance of spatial tasks such as wayfinding involves interactions between people and their environments. Although many models have been developed to conceptualise these interaction processes, and their impacts upon spatial behaviour, most emphasis has been upon human cognition and the impacts of prior knowledge upon behaviour. For reasons that are explored in this thesis, there has been rather less focus upon study of overt behaviour during the actual process of wayfinding.

Human wayfinding is often assisted by external aids such as maps, written instructions and devices (e.g. compass). Over the last decade, there has been rapid development of mobile information and communication technologies. The increasing storage capacities of mobile devices, the increasing bandwidth and availability of broadband wireless communication, and the growing volumes of location specific information are all inevitably leading to demand for services that can deliver location specific information to the individual on the move. Such services are generally known as Location-Based Services (LBS). Thus wireless mobile devices, such as mobile phones and wireless-enabled personal digital assistants (PDA), are providing new ways to deliver spatial information to the individual. Much of this information can be used to assist wayfinding. Consequently, a number of questions and challenges are being raised for wayfinding research. The means by which people acquire spatial information is inevitably changed when mediated by technologies - spatial information can usually be acquired in real-time, at any location. Spatial information can be accessed using mobile devices, in multiple communication modes, and in ways that are tailored towards individual needs. The acquisition of the information can be interactive and the content dynamically refreshed with updates. It seems axiomatic that these new ways of accessing spatial information are affecting the nature of human wayfinding, but we as yet understand rather little about these developments. Specifically, how can these technologies assist our understanding of the process by which spatial knowledge is acquired, valued, communicated and applied for completing wayfinding activities? From a different perspective, these technologies are also poised to impact the methods of spatial cognition research (Montello, 2001). Many of these issues are also at the core of geographical information science (Longley *et al.* 2005). Yet to date, the role of new technologies has not been assimilated into wayfinding research. Moreover, the pivotal role of mobile devices as sources of spatial information has not been considered in studies of interactions between people and their environments.

This research aims to investigate the real-time interactions and information transactions between individuals, their mobile devices and urban environments during pedestrian wayfinding activities. The technology element in the form of mobile devices is seen as a new and important element in the interaction between people and their environments. Thus, a conceptual model is proposed here which explicitly focuses on the interaction and spatial information transactions that occur (Chapter 5). Individuals, as one of the elements of the model, can access and acquire spatial information through a mobile device whilst acting and moving within the environment. They can also gain information directly from the environment. Mobile devices, as the technological element, act as interactive information sources. Spatial information delivered through the mobile device is derived from the environment. The wayfinding performance and the way by which spatial information is acquired by individuals can be influenced by their spatial abilities, prior knowledge and their social and cultural backgrounds. Such performance and spatial information acquisition are also likely to be influenced by the specific environments and contexts in which the wayfinding is taking place. In this research, individual spatial information transactions through the mobile device and the overt wayfinding behaviour are studied within the framework of this conceptual model.

A further strand to the novel methodological approach of this research concerns the ways in which real time interactions and spatial information transactions are captured through monitoring of individuals, mobile devices and environments. The approach consists of: a set of virtual reality (VR) environments, designed and implemented specifically for this research; a series of specially constructed wayfinding experiments; self-assessments of individual spatial abilities; and post-experiment evaluations of the test environment and the user interactions that it fosters. The VR-based test environment provides simulated real world urban wayfinding scenarios in an immersive virtual reality that allows individuals to 'walk around' at street level. The test environment was created using the following components: VR urban models; a simulated location-based service application using a mobile device as an information source; and software for recording participant actions and reactions within the test environment. The multi-source data collection includes movement tracking, recording of spatial information accessed through the mobile device, and detailed recording of participant actions. Crucially, the VR-based test environment is used to provide a stable and consistent setting for all participants during the wayfinding experiments. Furthermore, by using this approach, the overt interaction behaviour and real-time spatial information transactions can be recorded in a clearly controlled manner, and a rich data set is created.

A series of detailed empirical wayfinding experiments concerning geographically extensive areas have been carried out using this controlled setting and research design. The activities studied in this research centre upon urban pedestrian wayfinding using mobile device as information sources for assistance. The test environments seek to present distinctive contrasts between settings in terms of their mix of built features and street layout. They thus present tasks that highlight differences in participant wayfinding abilities, and differences in the nature of spatial information that is required to complete the specified tasks. This study makes no attempt to consider wayfinding in rural areas, and the mode of individual movement is restricted to pedestrian. The wayfinding experiments are task-based and involve travelling to a novel destination in an unfamiliar setting.

The attributes of the environment can have an important influence on wayfinding behaviour, and the VR-based approach allows such influences to be investigated in a systematic manner. This has entailed the creation of two contrasting urban models with their own distinctive layouts and mix of architectures: one of them is characterised by grid-like street patterns and modern low-rise housing; and the other is characterised by a more irregular layout with the features of a traditional market town. Both are based on real UK towns.

The empirical data on interactions and information transactions that have been generated by the wayfinding experiments have allowed a number of aspects of spatial information usage and wayfinding behaviour to be investigated. To begin with, the data make possible the investigation of wayfinding behaviour as expressed in route choice, distance travelled and time taken to complete wayfinding tasks in the two spatial settings. The spatial information usage via a mobile device during wayfinding has been measured and coded into a set of variables. One key focus has been on establishing patterns of spatial information usage preferences in terms of types of information, frequency of access, and time spent in consulting the information. The data have also allowed a classification of usage groups to be developed. This is further investigated in relation to the self-assessed measures of individual spatial ability. This is explored at both individual and group levels. Furthermore, all these aspects have been further explored in the two different urban settings in order to investigate the influence of urban morphology. In this way, original insights are developed into wayfinding using wireless mobile devices.

The arrangement of this thesis is as follows:

- In Chapter 2, the technological setting to the research is examined. A review is developed using a number of technological threads, including mobile telecommunication networks, mobile devices, positioning technologies and applications of Location-Based Services (LBS). The implications for research questions and challenges raised from the development of technologies are examined from the perspectives of LBS applications, human-devices interaction, wayfinding research, and GIScience and spatial information.
- Chapter 3 reviews some important aspects of human wayfinding and its constituent aspects of spatial acuity, spatial knowledge, spatial knowledge acquisition, methods of measuring spatial ability and human-environment interaction. The literature reviewed in this Chapter is derived from a range of different research disciplines, principally psychology, geography and GIScience. This review is organised thematically rather than from any traditional disciplinary perspective.
- Issues pertinent to using Virtual Reality (VR) as a part of the experimental test environment are reviewed in Chapter 4. This includes a review of the components and technical specifications of VR environments, and discusses previous research on issues of realism and presence. Important research on acquiring and learning spatial knowledge through VR environments is also reviewed and discussed.
- In Chapter 5, a conceptual model is proposed which brings into focus the interaction and spatial information transactions between three main elements: individuals, mobile

devices and environments. Challenges in implementing the conceptual model for studying interactions and transactions between these elements are discussed. A novel methodological approach is developed in this research and presented.

- Chapter 6 presents the design and set up of the wayfinding experiments. These consist of: compiling a pre-experiment questionnaire; creating a test environment with two VR urban models; simulating wayfinding assistance using a PDA and monitoring the ways in which it is used; and setting up a two-part post-experiment questionnaire. The design of the task-based wayfinding experiment is also described and explained. Finally, the implementation of a prototype for testing prior to conduct of the main experiments is presented.
- Chapter 7 describes the conduct of the wayfinding experiments including: a brief account of the preparatory work undertaken; description of the participants, the site at which the experiments were implemented and the equipment used; description of the two sets of task-based wayfinding experiments carried out in the VR test environments; and the design of the pre-experiment questionnaire and two-part post-experiment questionnaire. The procedure of data collection during the experiments is also explained.
- Chapter 8 describes the processes of data integration, data exploration and analysis. The research findings and discussion are also presented. The chapter begins with a description of the process of integrating the empirical data to create new data sets for analysis. Next, a classification resulting from the analysis of the pre-experiment questionnaire responses is presented and evaluated. Then follows an analysis of the responses to a post-experiment questionnaire designed to verify the sense of presence experienced in the VR environments. Also verified is the correspondence of the wayfinding strategies used by the participants in the VR environments as compared with their strategies in the real world. Next is an analysis of the spatial distribution of movement tracks and the derived variables of distance and time, and an analysis of the spatial information usage via the mobile device. A classification of individual spatial information usage is also presented. Finally, a number of case studies and qualitative discussions are presented at group and individual levels in respect of spatial layout and spatial information usage. The approach taken in this Chapter is to present results and findings in Sections immediately followed by discussions of the research findings.
- In Chapter 9, the conclusions arising from this research are drawn together and critically discussed. Based on these findings, a number of strands for future research are identified.

CHAPTER TWO
The Technological Setting

The rise of the knowledge society and the informational economy has been documented and discussed in detail, *inter alia*, by Castells (1989, 1996). We have become a "network society" founded upon modern information and communication technologies (ICTs). In the 1990s we saw the introduction of the World Wide Web and the ubiquitous uptake for business and recreational use of networked PCs, the Internet and mobile communications. This period also saw widespread development and use of the Global Positioning System (GPS) for positioning and Geographic Information Systems (GIS) for the organisation and visualisation of spatial data. The number of mobile ICT device users increased rapidly. By 2001, more than 40% of the population in Europe and nearly 70% in the UK owned a mobile phone with 700 million subscribers worldwide. The number of worldwide subscribers has probably tripled by 2005 (though there is little way of confirming current mobile phone ownership, such is its ubiquity). The increasing mobility of individuals, the availability of broadband communications for mobile devices and the growing volumes of location specific information available in databases are inevitably leading to the demand for services that will deliver location related information to individuals on the move. Such services are generally known as Location Based Services (LBS). A range of applications will be described in §2.2 including navigation services which are aimed at providing information through mobile devices to assist people's wayfinding activities.

In this Chapter, a number of technological threads will be discussed. These form the background to LBS and this research. The purpose of the discussion here is to identify some of the areas of research that arise as a consequence of this changed technological setting. In §2.1 the individual threads are discussed; in §2.2 location-based services and their applications are introduced; and in §2.3 a research agenda is identified which frames the overarching aim of this thesis.

2.1 Technological threads

For the purpose of the research to be undertaken, a distinction will be made between what has now become standard information and communication technologies infrastructure and what are referred to in this research as new information and communication technologies (NICTs). NICTs are differentiable by the following characteristics:

- use of mobile telecommunication networks;

- high-level communication protocols, such as Compact HTML (I-Mode), Wireless Application Protocol (WAP) and Extensible Markup Language (XML);
- handheld, mobile and small size wireless communication devices;
- location awareness;
- wide usage in business and social life.

Some of the important aspects of these characteristics are discussed in the paragraphs that follow.

The mobile telecommunication networks have developed rapidly from second generation to third generation and towards future fourth generation. The second generation (2G) networks have a bandwidth of 9.6 Kbps, and include the Global System for Mobile Communication (GSM), Code Division Multiple Access (CDMA) and Time Division Multiple Access (TDMA). The 2.5 generation (2.5G) networks include General Packet Radio Service (GPRS) with their increased bandwidth of 115 Kbps and Enhanced Data Rates for Global Evolution (EDGE) with bandwidth of 400Kbps. The fully implemented third generation (3G) networks could support a bandwidth of 2 Mbps, and include the Universal Mobile Telecommunication System (UMTS) and Wideband Code Division Multiple Access (W-CDMA). The fourth generation (4G) is predicted to have a transmission rate of up to 100 Mbps (Peng and Tsou, 2003). Such bandwidth would be ample for delivering location aware services and applications. Wireless Application Protocol (WAP) was first implemented as a communication protocol in 1997 and has been developed to facilitate the mobile Internet. The development of mobile telecommunications provides a combination of speed, coverage and mobile devices, and has also transformed service status from focusing on transmission of voice to various applications of transmitting multimedia information.

Over the last decade, the number of mobile device users has rapidly increased as the costs of devices and services have fallen. Mobile devices are widely used in business and social life. In this thesis, the term 'mobile devices' is used to refer to handheld, mobile and small size wireless devices such as Personal Digital Assistants (PDA) and mobile phones, which can be connected to mobile communication networks. Successive developments in mobile devices have engendered faster processors, additional options, and improved graphics capabilities such as colour screens and greater display resolutions. There are also hybrid systems integrating the capabilities of PDA and mobile phones in a single device. Figure 2.1 illustrates some of these mobile devices. With the development of location awareness technologies (discussed below) and increasing numbers of mobile device users, services providing location related information are likely to become an application of rapidly growing importance.

Figure 2.1 Examples of mobile devices and their protocols (WAP=wireless application protocol, MMS = Multimedia messaging, J2ME = Java2 Micro Edition), (based on Li and Maguire, 2003).

With the widespread use of mobile telecommunication networks and mobile devices, location awareness has become another important aspect of NICTs. A number of techniques are available for determining the position of mobile communication devices when they are in use. One class of positioning technologies is mainly based on mobile telecommunication networks, and is referred to here as network-centric methods; while another is satellite-based positioning technologies (i.e. GPS) and is referred to here as device-centric methods. There are also combined positioning technologies which integrate both network- and device-centric methods. The following are key positioning techniques (Sage, 2001; Giaglis et *al.*, 2002; Zeimpekis et. *al.*, 2003; Grejner-Brzezinska, 2004):

- Network Cell Identification (NCI) or Cell ID – this network-centric method identifies the approximate position of a mobile device through locating which base station the device is using at the given time. The accuracy varies from about 250 metres in urban areas to over 10km in rural areas depending on the cell size. There is no specific hardware and software support required for the mobile device. There are also two types of enhanced Cell-ID methods. One of them uses timing advance method to improve the location accuracy while another improves accuracy by using measures of the signal strength to estimate the distance between a mobile device and a current base station.
- Time of Difference Of Arrival (TDOA) – this network-centric method calculates the time difference of the transmitted signal from a mobile device arriving at three separate base stations. In theory, the locational accuracy of the TDOA method can be between

50 to 200 metres. However there is the need for high synchronisation within the network of base stations to support TDOA in a GSM network. There is no specific hardware and software support required for the mobile devices.

- Angle of Arrival (AOA) – this network-centric method measures the angle of the same signal arriving at two or more base stations. An array of antennas, instead of just the one antenna per cell, is needed for base stations to measure the angles. The accuracy of the AOA method is usually within 300m, however, it can be degraded significantly in rural areas. There are hardware support requirements for both the network and mobile devices.
- Global Positioning System (GPS) – this device-centric method works by including a satellite navigation receiver in a mobile device. The accuracy can be within 20 metres. However, it needs a clear view of the sky and signals from three or four satellites. Moreover, mobile devices with built-in GPS receivers have higher power consumption and shorter battery life. Assisted-GPS is required for covering situations such as in-building areas and tunnels as a second supplement signal.
- Enhanced-Observed Time Difference (E-OTD) – a device-centric method which calculates the time taken for a signal to arrive from at least three base stations. The method requires installed software on the mobile device. The accuracy is about 50 metres. It can also be a network-centric solution as a modification of TDOA method explained above.
- One hybrid method is GPS in conjunction with TDOA/AOA - this solution works through GPS-enabled handheld mobile devices supplemented by Cell-ID, TDOA or AOA. The method, however, may create incompatibility as there is no standard for doing this amongst mobile network operators.

A wide range of applications is emerging based on such technologies, from delivering various information and services, tracking and managing fleets and mobile commerce to games and (in the future) digital TV delivered to the mobile phone. One such application for delivering location related information to individuals, LBS, has substantial relevance to this research and will be discussed in detail in the following Section.

2.2 Location-based services (LBS)

Location-based services (LBS) entail "the delivery of data and information services where the content of those services is tailored to the current or some projected location of the user" (Brimicombe and Li, 2006). Such information and services are provided to users by their mobile devices. LBS can be seen as the convergence of NICTs (discussed in §2.1), the Internet, GIS and spatial database as illustrated in Figure 2.2.

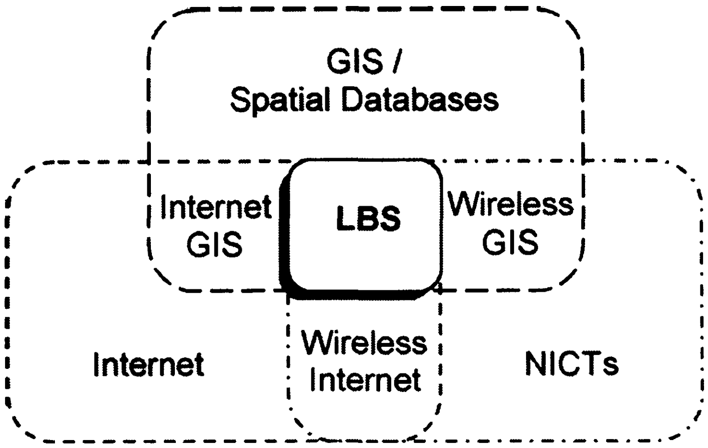


Figure 2.2 Convergence of technologies (from Brimicombe and Li, 2006).

The Internet can be regarded as a ubiquitous source of information and distributed services across networks, whereas the NICTs discussed in §2.1, provide capability for mobile access/delivery with location awareness. The other main area in Figure 2.2 is GIS which can be considered a mature technology for integrating, managing, analysing and visualising spatial data. Geographical information services have been offered over the Internet to provide data and processes on demand to distributed users through Web browser interfaces. Major GIS software providers also offer versions of their products for mobile handheld devices, giving rise to wireless GIS (Braun, 2003). These GIS applications provide the ability to deliver data, computing capability and integrated functionality to individuals at distributed locations. LBS have only been made possible by the development and convergence of these technologies.

One of the main drivers of LBS was the U.S. Federal Communications Commission's adoption of the enhanced 911 (E911) mandate. The E911 mandate aimed to improve the quality and reliability of the emergency services by being able to locate wireless 911 callers (Federal Communications Commission www.fcc.gov/e911/). The benefit of the E911 mandate is that it provides the basis for a wide range of additional, value-added location based services. In Europe, the concerns of locating wireless emergency calls only started to be tackled in 2000. Nevertheless, there has been fast development and deployment of both wireless and location-aware networks. The provision of location based services in Europe is driven by the motivation to provide differentiating and value-added services in a competitive marketplace. From the middle of 2003, European registration requires network operators "to determine and forward the most reliable caller location information available for all calls to the single European emergency call number 112 (The Commission of the European Communities, 2003).

With considerable growth potential in location-based services, a range of applications has been identified and are discussed here. All of these concern the delivery of information and services to users on the move via their mobile devices. User-solicited services provide location specific information for business and social purposes. For example, local public transport options, traffic information and availability of local services can be delivered to users on the move in real-time whenever required. Pushed services are the delivery of unsolicited information to users' mobile devices, such as proximity-related advertising and warnings. Another category of LBS applications emphasises services related to real-time tracking, such as managing vehicle fleets, or knowing when a friend or family member is nearby or at certain locations. This can include instant messaging services which can be used for communicating with people within the same or nearby localities. LBS can also be used for co-ordinating emergency services in responding to accidents and disasters. Future applications may well include commercial services directly related to a user's current location, such as location-based tariffs and pay-as-you-go car insurance.

One of the important services which LBS offer is providing information to people for exploring areas, planning routes and directing them to reach destinations. In-car navigation systems, as one example, can identify shortest route or fastest route given a start point and a destination point. Information is often given as route maps and/or sequential instructions. As another example, maps and/or instructions can be given through mobile devices to orientate and direct individuals to arrive at their required destinations. A range of input and output methods has been proposed and offered, and some applications seek to identify the desirable and more effective ways of delivering information. Voice has been suggested as a user-friendly method for inputting requests and giving instructions. Using speech via mobile phones to provide navigating instructions during driving is just one example. Three-dimensional or graphical images are being investigated for use in other applications.

Another aspect of LBS currently being researched focuses on adapting content to user needs. Here the emphasis is upon how to obtain and interpret the location and context information from the environment and from users. For example, user-adaptive content for LBS applications have been studied as a means of ascertaining users interest and preferences in areas such as map display for different countries, presentation of mapped zones with different levels of generalisation, and adaptation to user orientation (e.g. Zipf, 2002).

Brimicombe and Li (2006) outline a publisher and subscriber model to adapt information content based on location and context so as to maximise utility to the user. Furthermore, interactivity between a mobile computing device and its user has been studied with consideration of device ability to obtain and interpret contextual information for user benefit (Dey, 2001; Schmidt & Van Laerhoven, 2001).

2.3 Implications for research questions and challenges

2.3.1 LBS applications perspective

As discussed in the previous Section, LBS applications aim to provide locational information and services for people's need. Although the information and services can vary, the main concerns are delivery of more relevant, timely information to people on the move. The emphases of current applications have been on the technical capability and the diversity of mobile devices to deliver and access locational information. The focus is also on the effectiveness and user friendliness of the mode of delivery of such information and services, such as "speak and listen", maps, text and multi-media. For example, some applications for wayfinding assistance provide a number of different interfaces by which users can access locational information. Such systems can navigate people by the use of textual information or voice instruction. Information can also be delivered to mobile devices in combined formats, such as maps with calculated routes, or graphics with text. All along, an important consideration of these applications must be to provide pertinent and timely information to users. Therefore, the question arises as to what information is likely to be relevant in any given situation and how should it best be communicated to the users? The use of detailed personal profiling, precise user location and user movement history have been suggested and discussed as a means of ensuring greater relevance (Mountain & Raper, 2001; Fogli *et al.*, 2003).

Such emphases on improving information content have largely overlooked issues of individual spatial abilities. To date, little systematic research has been carried out regarding individual's cognitive abilities, spatial awareness and other related skills in accessing and using LBS applications. Moreover, few studies on the design and implementation of applications for assisting wayfinding have been based on an understanding of wayfinding research.

2.3.2 Human-computer interaction for mobile devices perspective

With the availability and continuing development of mobile devices, there has been research interest into human computer interaction for mobile devices over recent years. This field of research is often referred to as mobile human computer interaction (mobile HCI). Human-computer interaction research has focused upon understanding the ways in which humans interact with computers, aiming to have a system to satisfy user needs and requirements in terms of system functionality and operation (Nielsen, 1993; Preece *et al.*, 1994). With an increasing number of applications using mobile devices (e.g. LBS), mobile HCI research gives more emphasis to human-device interaction in terms of developing mobile context-aware applications (Borntrager *et al.*, 2003). Kjeldskov and Graham (2003) have reviewed a number of mobile HCI research methods. They note a tendency of the research towards building systems and lack of emphasis on understanding design and usage which is limiting knowledge development in this area. Thus, the majority of the research tends not to address the question of what is useful from a user perspective. Approaches have tended to be laboratory-based, and whilst interaction between human and mobile devices can be studied in detail, the surrounding environment has not had a significant role.

In general, the interaction between users and mobile devices can be viewed as a new kind of human-computer interaction. In conventional desktop based human-computer interaction, the surrounding environment is under-represented in the research. For mobile human-computer interaction, the surrounding environment has started to be brought into consideration, for example by directly observing the phenomena and people (Oulasvirta *et al.*, 2003; Paay, 2003). However, the surrounding environment has not been regarded as a mutable information source with which people are interacting. Therefore, there has been no explicit focus upon the dynamic interactions between individuals, mobile devices and environments.

2.3.3 Wayfinding research perspective

There has been extensive research on wayfinding, which will be discussed in detail in Chapter 3. Research has been carried out aimed at understanding people's spatial behaviour and the differences amongst individuals (Lloyd, 1989; Gopal & Smith, 1990; Golledge & Stimson, 1997; Allen, 1999). Much of this work has focused on the nature of cognitive maps as internal spatial representations, as well as how they are developed and how information is acquired for performing spatial activities. When encountering a new environment, people are likely to need a range of information for completing spatial tasks such as wayfinding. People acquire and develop their spatial knowledge through various experiences and processes, which may include recognising and understanding characteristics of objects, localities and inter-relationship between elements in environments. Spatial knowledge can be acquired in different forms (Siegel & White, 1975; Kuipers, 1978; Thorndyke & Hayes-Roth 1982; Golledge & Stimson, 1997). Interaction between people and the environment has also been researched from cognitive perspectives over several decades. A range of conceptual models or schema has been established to understand how people structure and develop an inner representation through recording and processing of information based on their perceptions of the real world and inferences about it (Downs, 1970; Pocock, 1973; Gold, 1980; Golledge & Stimson, 1997).

With the wide usage of NICTs and the development of LBS applications for assisting wayfinding activities, a number of questions and challenges are being raised for wayfinding research. The means by which people acquire spatial information is inevitably changed when mediated by technologies - spatial information can be acquired in real-time, at any location. The information can also be provided in a range of forms such as different scale of maps, text and/or voice route instructions, graphics and other multi-media forms. Mobile devices can be used to access real-time dynamic locational information. All of these differ from traditional ways of accessing spatial information to assist wayfinding. Thus, the technologies and the availability of location-based information and services pose research challenges for our understanding of cognitive processes and spatial knowledge acquisition. How such information is provided and the way by which it is delivered is likely to have an influence on the acquisition and development of spatial knowledge. In addition, individual differences in spatial ability and behaviour should be considered in LBS applications. Importantly, how can these technologies assist our understanding of the process by which spatial knowledge is acquired, valued, communicated and applied for completing wayfinding activities? On the other hand, these technologies are also poised to impact the methods of spatial cognition research (Montello, 2001). Yet to date, the role of technology has not been included in wayfinding research. Moreover, mobile devices, as information sources, have not been considered in studies concerning interactions between people and the environment.

2.3.4 GIScience and spatial information perspective

The continuing development of NICTs and LBS provide the technological setting to enhance and change the ways people access and utilise spatial information. Geographical information services (GIServices) can be considered in both a traditional mapping sense (e.g. through the Internet and WWW) and at a conceptual level using NICTs. The applications of GIServices can be performed at a remote site, which allow the user to take advantage of remotely located data and services through their devices, and which provide ways of combining information gathered through the senses with information provided from digital sources (Longley *et al.*, 2005). Applications of GIServices continue to grow steadily, but are to some extent restricted by current technical impedances arising from limited communication bandwidth and reliability (particularly in densely-built urban settings), and the constraints of battery technology. Still greater impediments arise out of user difficulties of interacting with devices in field settings. The convergence of technologies discussed above could lead to the ubiquitous GIS through mobile geographic services and a focus on individuals in mobile contexts (Li and Maguire, 2003).

From a GIScience perspective, a shift from generic to user-centred mapping is one of the important challenges (Longley *et al.*, 2001). Given that the demand for real-time, fast-changing information is increasing, NICTs will mean that people will be able to receive more relevant, timely information in various forms. Personal needs are also being increasingly emphasized. But what information do people require, and consequently what kinds of data are needed? The dynamics and complexity of the urban arena present another consideration. This is in regard to mobile users accessing information whilst being located in real time within the environment to which the information pertains. In these situations then, what constitutes relevant and meaningful information? The conventional means of communication of spatial information has been the map and most GIS are conventionally designed to deliver map-based solutions. Within LBS the map is likely to be only one mode of information communication. How might the modes of communication evolve, particularly if they are to enhance people's ability to acquire spatial knowledge?

Another area requiring research is the semantics of communication between individuals and a database with or without the intermediary of a call operator. In navigation LBS applications, instructions are given to people by means of maps, spoken word and text. It is envisaged that various landmarks, points of interest (POIs) and key features of neighbourhood environments might be provided as spatial cues via mobile devices. On the other hand, people's ability to answer spatial questions may be limited either through lack of awareness or confusion over vocabulary and map reading. This strikes at the traditional core principles of GIScience such as data modelling, data handling, generalisation and visualisation. Can objects be described in terms of neighbouring features in exactly the same way that people might describe them after looking at a map? The precise relation of cognition to language remains controversial (Mark, 1999). Can we arrive at a common semantic for spatial descriptive terms between systems and people when they are receiving information through handheld mobile devices in the field?

What has come to light in this Chapter is a considerable research agenda that has been prompted by the introduction of mobile devices for spatial information query and delivery into wayfinding tasks – more than can be addressed within this thesis. Moreover, many of the interwoven issues are real in as much as they have been triangulated from the perspectives of different disciplines. In this setting, the overarching aim of this thesis is to investigate aspects of urban pedestrian wayfinding using mobile devices that fall within this wider research agenda. In Chapter 3 the relevant research review is put forward and the specific research objectives for thesis refined.

CHAPTER THREE
Wayfinding, Spatial Information and Interactions

As discussed in Chapter 2, the development of new information and communication technologies has had profound effects on many aspects of our post-modern society. From the perspective of the research being presented here, technologies such as the World Wide Web (WWW) and mobile phones have mediated the ways in which spatial information is being delivered to the individual. This in turn is likely to impact upon the ways in which people are able to access spatial information in real-time and whilst on the move. Thus, services such as LBS for wayfinding, delivered to location-aware mobile devices with a more individual focus, are now a real possibility. These developments are pertinent to the study of people's spatial abilities, and the ways in which they acquire and develop spatial knowledge. In addition the interaction between people and the environment during wayfinding now needs to be understood in conjunction with this further technological dimension.

This Chapter presents the literature review on human wayfinding and its constituent aspects, spatial acuity, spatial knowledge, methods of measuring spatial ability and spatial knowledge acquisition, and human-environment interaction. The research in these areas comes from different research disciplines, principally psychology and geography. However, rather than take a strictly disciplinary approach to the review, the discussion is organised thematically. In the penultimate Section, a GIScience perspective is presented.

3.1 Human wayfinding

Wayfinding is one of the basic spatial activities which people frequently experience when they interact with environments. The term 'wayfinding' can be regarded as the process in which paths/routes are identified, determined and followed between an origin and a destination (Bovy and Stern, 1990; Golledge, 1999). Wayfinding is differentiated from navigation as being different types of activities, although these two words have been used indistinguishably in some papers. Navigation is formally defined as to "manage or direct the course of (a ship, aircraft etc.)" (Fowler and Fowler, 1995), whilst it can colloquially mean to walk or make one's way deliberately through some place and is often referred to as "the science of locating position and plotting a course for ships and aircraft" (Golledge, 1999). Wayfinding is described as purposive and motivated movement towards a specific and distant destination that cannot be seen directly by the traveller (Heft, 1983; Garling *et al.*, 1984;

Blades 1991; Golledge, 1992). In this thesis, the term 'wayfinding' is used for the process just described. Downs and Stea (1973) define four stages in wayfinding activity, which are:

- orientation to determine self-location and estimated target-location;
- initial route choice in selecting routes from origin to target-location;
- route monitoring, that is, checking the route taken by estimates of self-location and target-location as well as reassessing / confirming the route choice;
- recognition of the target.

Golledge (1999) has subsequently suggested what necessitates successful wayfinding tasks:

- identifying origin and destination;
- determining turn angles;
- identifying segment lengths and directions of movement;
- recognising routes and distant landmarks; and
- embedding the routes taken into a larger reference frame.

There are three general types of wayfinding tasks which can be categorised according to their functional goals (Allen, 1999a). The commute type of wayfinding concerns travel between a known origin and a known destination along familiar routes, such as a commuter's daily travel to work. This type of wayfinding activity usually has low uncertainty and involves a high-level of routinised behaviour. The exploratory type of wayfinding considers the activity of exploring a surrounding environment starting from a familiar origin and returning to a known destination (often the place of origin). In such wayfinding activities, people reconnoitre with the aim of discovering new places, routes and areas. There is a certain level of uncertainty involved in both the relation between current position to familiar places and the usefulness of the information received. Task-based wayfinding, which also refers to quest type of wayfinding, involves travelling to a novel destination from either a known origin or an unfamiliar place. During this type of wayfinding task, there is a higher level of uncertainty. There is likely to be a variation in the traveller's confidence in relating current position to final destination over the course of the task. Compared with exploratory type wayfinding, task-based wayfinding activities require higher levels of ability to comprehend all the information received. This last type of activity is often assisted by the provision of spatial information either in a symbolic form such as maps or in a description such as route instructions.

Wayfinding is interactive behaviour between people and their environments. The attributes of both people and their environments influence how and how well wayfinding is achieved (Allen, 1999b). Such interaction between people and environment is described by Tuan (1977) in a situation of getting lost, in the dark, during wayfinding:

> "Space is still organised in conformity with the sides of my body. There are the regions to my front and back, to my right and left, but they are not geared to external reference points and hence are quite useless. Front and back regions suddenly feel arbitrary, since I have no better reason to go forward than go back. Let a flickering light appear behind a distant clump of trees. I remain lost in the sense that I still do not know where I am in the forest but space has dramatically regained its structure. The flickering light has established a goal. As I move towards that goal, front and back, right and left, have resumed their meaning..."

Furthermore, wayfinding is viewed as entailing spatial problem solving processes for finding one's way to a destination, and consists of the three interdependent processes of decision making, decision execution and information processing (Arthur and Passini, 1992). During wayfinding activities, travellers are in a sequential process of decision making in which the purpose is to match internal with external information as it is obtained (Stern and Portugali, 1999). During wayfinding activities, the environment is a dynamic source of information used by travellers in their decision-making processes. Lynch (1960), in his seminal work, suggests that "there is a consistent use and organization of definite sensory cues from the external environment" during wayfinding. He emphasises the way that humans structure mental images of the city about landmarks, nodes, paths, edges, and districts. It is important to understand and know the external environment during wayfinding activities. However, there is a clear consensus that differences exist between the environments that people perceive subjectively and the objective reality, and the way people acquire, develop and use cognitive information for their wayfinding activities (Golledge, 1999). Cognitive information or cognitive maps are regarded as the internal representation of the structure, entities and relations of space (Hart and Moore, 1973), and are viewed as devices for simplifying and conceptualising the complexities of human-environment interactions (Walmsley *et al.*, 1990; Golledge and Stimson 1997).

Since wayfinding is purposive behaviour involving people and environment, another important aspect of wayfinding is the individual's spatial ability for carrying out such activities. Individual differences in spatial ability will have an effect on spatial knowledge acquisition during wayfinding and hence the success of wayfinding activities. Furthermore, human wayfinding is often assisted by external aids such as maps, some forms of instructions and devices. As discussed in Chapter 2, mobile devices have provided a new way to deliver spatial information which can be used for assisting wayfinding. Spatial information can be accessed, in multiple communication modes, with more individual emphasis. The following Sections will discuss these aspects in detail, focusing on spatial ability, spatial knowledge acquisition, human-environment interactions and spatial information which are particularly related to this research.

3.2 Spatial acuity

People move about and interact in space and places in daily life. Spatial information comes from direct sensory experience such as the senses of touch, balance, hearing and our own sense of movement as well as indirect conceptual experiences such as interpersonal and mass communication (Banz, 1975; Gold 1980; Berthoz *et al.*, 1995). Spatial ability develops as one grows up and increasingly sophisticated spatial knowledge can be developed in the later stages of human development. The meaning which people attach to space and place is complex given the variety of human spatial abilities, environments and social-cultural backgrounds (Tuan, 1977). According to The Concise Oxford Dictionary (Fowler and Fowler, 1995), there are nine definitions of *space* as a noun and three more as a transitive verb. Space and place can be viewed as a semantic sequence as illustrated in Figure 3.1.

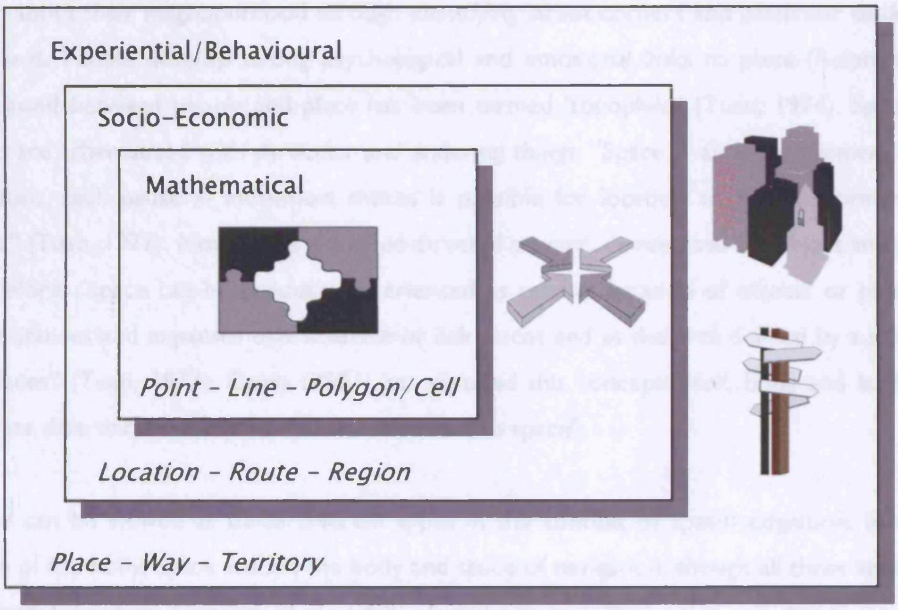


Figure 3.1 Semantic sequence of space and place (Brimicombe, 1999).

Space, when considered at its most objective, is a mathematical, physical space of co-ordinate geometry. The primitive elements, as used in GIS, are *point*, *line* and *polygon* or *cell*; and their spatial relations are a matter of topology. At a socio-economic level, the neutrality of objects in mathematical space is replaced by attributes of superiority or inferiority for some purpose (Brimicombe, 1999). Thus a location can be considered to have both site and situation resulting from the spatial relations that emerge between consumers, producers, labour and raw materials. At this level the primitive elements are translated into *locations*, *routes* and *regions*. Social and business interactions and transactions necessarily occur in some location or are communicated between locations. Finally, in the experiential/behavioural domain, the spatial primitives are further translated into *place*, *way* and *territory* through an infusion of human meaning. Here space and place are defined and mediated through human activity and the construction of meaning. The phrase 'environment' as used in this thesis encompasses this range of meanings of space and place. The term 'spatial acuity' as used here encompasses the whole gamut of spatial ability and people's innate sense of space and place.

3.2.1 Sense of space and place

Tuan's (1977) seminal work on space and place refers to space as abstract, openness, freedom, allowing movement in comparison with place as its identity, stability and familiarity. Space can be turned to place when people feel familiar with the space and endow it with value. Place can been viewed as a type of object. Human beings recognise and become familiar with particular objects, and attach feeling to them, such as the ways in which people learn about their neighbourhood through identifying street corners and particular landmarks within it. People develop strong psychological and emotional links to place (Relph, 1976). The bond between people and place has been termed 'topophilia' (Tuan, 1974). Space and place are schematised with particular and enduring things. "Space allows movement, place is pause, each pause in movement makes it possible for location to be transformed into place" (Tuan, 1977). Movements are often directed toward, or repulsed by, object and places. Therefore, "space can be variously experienced as relative location of objects or places, as the distances and expanses that separate or link places and as the area defined by a network of places" (Tuan, 1977). Casey (2001) has restated this concept: "self, body and landscape address different dimensions of place in contrast to space".

Space can be viewed as three different types in the context of spatial cognition, including space of the body, space around the body and space of navigation, though all three appear to be used seamlessly (Tversky *et al.*, 1999). Tversky *et al.* (1999) point out that these three spaces are conceptually different and serve different functions as people interact with them. Thus, space of the body concerns the motions and feeling of our bodies, which are essential to our basic life and survival. Space around the body is one's immediate surroundings organised into a mental framework based on body axes. Space of navigation refers to environments schematised to nodes and links (representing landmarks and routes) and their spatial relations, though frequently from a specific perspective (Lynch, 1960; Kuiper, 1978). When the space of navigation is conceptualised as a two-dimensional map, the schematisation results in loss of detail thus permitting efficient memory storage, but the loss of detail also results in distortion.

The sense of space and place differs with the cultural background and living environments of people. Human groups vary widely in spatial skill and knowledge. Culture, within which human beings develop, strongly influences people's behaviour and values. This is suggested through research and empirical evidence. Studies show that the contrast in physical environments and the different social structures give people different senses of space and place, spatial awareness and knowledge (Berry, 1966; Gladwin, 1970; Lewis 1972; Hazen, 1983). However, there are also shared traits in human beings that transcend cultural particularities and may therefore reflect the general human condition. Some studies have pointed out the universal aspects of spatial cognition (Appelle, 1972; Shepard and Hurwitz, 1984; Wallace, 1989). Some argue that cultural commonalities are more significant in spatial cognition than the cultural differences, and many apparent differences are more likely caused by other factors (such as training, expertise and social classes) within cultures other than cultural differences (Montello, 1995). The evidence for substantial culture differences in spatial cognition are then suggested as showing the differences primarily between traditional and technologically developed culture rather than the differences that exist between cultures. Intuitively, we believe that the cultural differences exist and emerge. Current studies do not seem to prove how significant they are. Both the cultural commonalities and differences in the sense of space and place are widely recognised, however there remains the question of how substantial the influence of cultural difference is upon spatial knowledge acquisition.

Information environment and the 'invisible landscape' were considered to be important from as early as the 1960s and 1970s (e.g. Stea, 1967; Gould 1975). With rapid developments in computing, the Internet, World Wide Web and mobile wireless telecommunication technologies over the last two decades, a new kind of space is infusing into social, cultural and economic life. This new kind of space, referred to as cyberspace, has been discussed in the literature (e.g. Castells, 1989, 1996; Batty, 1990, 1993; Graham, 1998; Kitchin, 1998; Dodge and Kitchin, 2000). Cyberspace may evolve to become equally important as physical space and traditional notions of geographical space. The trend is towards cities becoming informational places, mediated through electronic networks (Castells, 1989; Batty, 1990, 1993). Three possible futures for the inter-relationship between geographical space and cyberspace are discussed by Graham, (1998):

- *Technological determinism*: this assumes that new telecommunications technologies will directly cause social and spatial changes in which distance effectively dies as a constraint on social, economic and cultural life. This would result in areal uniformity and urban dissolution into a global village. This theory has perhaps grossly over-estimated the extent to which aspatial networks might substitute for place-based or face-to-face interactions.

- *Co-evolution of geographical and electronic spaces*: this suggests that we will continue to have physical and localised existences. Computer networks are a predominantly metropolitan phenomenon developing out of the old cities allowing the social reconstruction of city spaces. Thus materially constructed urban spaces co-evolve with telecommunication networks and nodes. Space is becoming recast by the interaction of capital and technology.
- *Actor-network constructs of space*: there is not one single, unified cyberspace, but is a fragmented, divided multiplicity of heterogeneous infra-structures and actor-networks. Space is no longer an objective, invariant external container for place with space being continually reconstituted by the actors on the network. The experience of place can thus be both real and virtual - it becomes impossible to define space and place separately from technological networks.

The increasingly widespread usage of NICTs and the integration of NICTs into people's daily lives increase the types of interactions among individuals, technologies and environments (space and place). Such rapid development of NICTs is allowing new combinations of people, technologies and places which may lead to a dramatic change in the spatial organisation of activities within cities (Moss and Townsend, 2000). The characteristics of some activities in people's lives are being changed with the advent and diffusion of such technologies. Moss and Townsend (2000) identify the need to study the effects of new telecommunications and information technologies on commuting, home, work and public spaces. The 'CoolTown' project being carried out in HP Labs (U.S.A.) and 'Mobile Bristol' (U.K.), are aimed at establishing effective relationships between our physical world and an informational virtual world. The linkages created between them could perform "roles in augmenting their counterparts across the physical-virtual divide" (HP, 2001) to produce a mixed-reality. In this way, technology is changing traditional concepts of space and place.

3.2.2 Spatial ability

Individual differences in performing wayfinding tasks are generally considered to be related to people's spatial abilities. Spatial ability carries a variety of connotations from different perspectives and disciplines (Allen, 1999b). From a psychometric perspective, the studies carried out on people's spatial abilities focus on the ability to perceive, remember and mentally transform figure stimuli (McGee, 1979; Lohman, 1988). Visualisation, speeded rotation (spatial relations between objects) and spatial orientation are the three most widely used spatial factors, which mostly involve mentally manipulating shapes, solving mazes, and finding hidden figures. Some of these are described in the following paragraph. Spatial ability has also been studied from an information-processing perspective. This approach is driven by task analysis in general, that is, attempts are made to characterise cognitive processes in terms of a set of constituent parts. Thus the types of analyses include visualisation and mental rotation, as incorporated into psychometric tests, visual-spatial memory, mental imagery, and spatial perspective-taking and orientation (Allen, 1999b). Research in spatial ability from a developmental perspective covers a wide range of aspects, similar to the areas from the information processing perspective, with emphasis upon the development/improvement from early to late childhood. Another perspective for studying spatial ability is from neuropsychology which mainly concerns the correlation between cognitive or behavioural dysfunctions and specific neurological damage.

Three main dimensions of spatial ability have been suggested from a psychological perspective: spatial visualisation, spatial orientation and spatial relations (Self *et al.*, 1992; Golledge and Stimson, 1997). Spatial visualisation concerns the ability to mentally rotate, invert and manipulate visually presented 2D and/or 3D objects. It is widely applied to many studies and is regarded as an important factor in comprehending geometric structures. Psychometric paper-and-pencil tests have been used in most spatial visualisation studies. Some have employed this dimension to examine the differences in spatial ability between male and female (Masters and Sanders, 1993; Stumpf, 1993), whilst others have argued that a single such dimension cannot be used to account for over-all spatial ability (e.g. Self and Golledge, 1994).

Spatial orientation, as another dimension of spatial ability, relates to the ability to imagine the configurations of objects as they would appear from different perspectives. This ability involves distance and angle estimation and orientation-related pointing accuracy, which is viewed as being important in map reading and wayfinding. The third, spatial relations, dimension of spatial ability is less clearly defined and sometimes is not included in the dimension of spatial ability from a psychometric standpoint. It includes a wide range of elements, from abilities to recognise spatial pattern, layout, and connectivity, through to wayfinding ability in the real-world with regard to landmark cognition, shortcutting and orientation. There are limited studies and tests on these aspects from a psychology perspective.

Spatial ability can also be studied and identified according to its relation to a common function (Rosch and Mervis, 1975). Allen (1999b) divides different types of spatial ability into three groups: a stationary individual with manipulable objects; a stationary or mobile individual with moving objects; and a mobile individual with large stationary objects. In the first situation, the focus is upon the ability to recognise objects based upon their constituent features, and concerns the interactions between individuals as observers and objects which can be rotated, disassembled and manipulated visually and mentally. This type is very similar to the spatial visualisation dimension of spatial ability. The second type concerns the dynamic spatial skills required to estimate objects' velocities or trajectories, and concerns the spatial relations between individuals (stationary or moving) and moving objects. The third type of spatial ability concerns mobile individuals interacting with a surrounding environment consisting of large objects. This last type of spatial ability is more directly related to wayfinding activities. Differences between individuals in assimilating knowledge about a spatial layout may arise from differences in identifying and remembering environmental objects long enough to establish their spatial relations, together with the variable capability to create the spatial relations between objects and reference points. Furthermore, individual differences can also reflect knowledge and skills in communication of spatial information such as by cartographic, symbolic or linguistic means.

As discussed above, individuals differ in identifying environmental objects and learning spatial relation and layout. Thus, the contents of individual internal representations of external environments, often referred to as cognitive maps, would be different. Such differences would also exist in the process of cognitive mapping. Cognitive mapping is defined as a process consisting of a range of psychological transformations through which individuals acquire, store, recall and decode information relating to locations and attributes of spatial environments (Downs and Stea, 1973). Types of spatial knowledge and the ways in which they are acquired (see §3.3) might also reflect individual differences. On the other hand, the data acquired rather than the cognitive mapping processes may differentiate spatial learning between individuals (Allen, 1999b). Thus the way in which individuals understand the spatial information of the environment such as distance and direction might vary according to their processing speed, working memory capability and experiences.

Although psychometric testing has been used in many studies to measure spatial ability, a number of studies point out that the spatial abilities identified through such tests exhibit only a weak positive association with the performance of spatial tasks in geographic-scale spaces, such as real-world environments (Lorenz & Neisser, 1986; Bryant, 1991; Allen *et al.*, 1996;). Other studies that address variation in spatial ability are more focused on relating large-scale environment task performance such as map and route learning, to real-world wayfinding activities (Malinowski and Gillespie, 2001; Kato and Takeuchi, 2003). Spatial abilities in geographic-scale spaces involve spatial tasks such as wayfinding to unfamiliar destinations and learning the layout of a new environment. How well people recognise objects and scenes from a learnt environment, estimate route distance, retrace routes, identify pointing direction, and comprehend the layout of the environment have all been used to measure spatial ability (Evans, 1980; Gärling and Golledge, 1987; Spencer *et al.*, 1989). Another promising approach for predicting people's spatial ability in geographic-scale space has entailed use of self-reporting questionnaires. A number of studies have reported high correlations between such self-reported measures and environmental spatial task performance (Montello and Pick, 1993; Prestopnik and Roskos-Ewoldson, 2000; Sholl *et al.*, 2000). Other issues that have been included into this type of self-reported questionnaire have concerned general abilities such as judging distances, finding one's way and shortcuts, and map reading. Similar correlations between these self-reported measures and spatial task performance in geographic-scale environments are also found in several studies (Byant, 1982; Lorenz & Neisser, 1986; Hegarty *et al.*, 2002).

3.3 Spatial knowledge

Study of the nature of spatial knowledge and how spatial knowledge is acquired, developed and used gives insight and understanding into how people behave and navigate while they interact with the environment. It also provides insight into individual and group commonalities and differences in spatial ability. Furthermore, it provides better understanding of the use of spatial information for assisting people in performing spatial tasks.

3.3.1 A typology of spatial knowledge

Knowledge can be distinguished as two types: *codified* and *tacit*. "Knowledge is codifiable if it can be written down and transferred relatively easily to others. Tacit knowledge is often slow to acquire and much more difficult to transfer" (Longley *et al.*, 2001). Knowledge of space and place is both codifiable and tacit.

Spatial knowledge allows individuals to "create large and complex schemata that exceed by far what an individual can encompass through direct experience That knowledge is transferable to another person through explicit instruction in words, with diagrams, and in general by showing how complex motion consists of parts that can be analysed or imitated" (Tuan, 1977). People's spatial knowledge structures are generally viewed as providing the basis for interpreting places in the environment. Spatial knowledge structures are a subset of an individual's knowledge of the environment. A knowledge structure, from the perspective of information processing, is also viewed as a set of symbolic structures representing certain aspects of an individual and the individual's environment (Golledge, 1987).

Spatial knowledge has been classified into different types in various research over the decades, including ego-centric and domi-centric knowledge (Trowbridge, 1913), strip map and comprehensive map knowledge (Tolman, 1943), and topological / projective / Euclidean knowledge (Piaget and Inhelder, 1956). The concepts of route and survey knowledge, and of landmark/route/configurational knowledge can been seen in the research of Shemyakin (1962) and Seigel and White (1975). Kuipers (1978, 1983a, 1983b) suggests sensorimotor, topological and metrical knowledge. Thorndyke and Hayes-Roth (1982) use procedural and survey knowledge. Stern and Leiser (1988) identify three levels of spatial knowledge in landmark, route and survey knowledge. Golledge and Stimson (1987; 1997) contend that spatial knowledge comprises three basic components including declarative component, relational/configurational component and procedural knowledge.

Although different types of spatial knowledge have been defined, they are each in turn generally deemed to fall within one of the following categories:

- *Declarative knowledge*: this type of knowledge refers to those objects and/or places with meaning or significance attached to them (Golledge *et al.* 1987). It is also referred to as landmark knowledge, frames of reference (Minsky, 1975; Kuipers, 1978) or cue knowledge.
- *Procedural knowledge*: this concerns understanding of the process of how to travel or find one's way from one locality to another, and can also be defined as route knowledge. Route knowledge typically refers to knowledge about movements and mostly consists of procedural descriptions, some landmarks and path elements.
- *Configurational knowledge*: This generally refers to the integrated knowledge of the layout of a space and the interrelationship of the elements within it, and people's ability to traverse in complex configurations of paths and nodes within some external frame of reference. This knowledge is considered to comprise not only visual and geometric, relational, perceptive and descriptive information, but also spatial relations. Survey knowledge, relational knowledge and metric knowledge are generally deemed to be in this category. Configurational or relational knowledge, in particular, refers to knowledge about spatial relationships between objects or places, and allows people to develop other knowledge structures including hierarchical networks and 'chunking' of knowledge (Golledge *et al.* 1997). Configurational knowledge has been defined as comprising of several characteristics as follows (Golledge *et al.*, 1995):
    - sets of identifiable 'occurrences' of spatial phenomena, such as landmark knowledge and routes linking them;
    - knowledge of the spatial distribution of such 'occurrences';

- the spatial processes that facilitate the integration and understanding of phenomena;
- spatial contiguity and association;
- linkage and connectivity; and
- geographical regions and spatial hierarchies.

Knowledge relating to 'areal' information, denoted as map-like knowledge, has been defined separately from configurational / survey knowledge in some of the literature (Aitken and Prosser, 1990). Configurational knowledge refers to the concept of 'sense of direction' (Kozlowski and Bryant, 1977), while areal knowledge focuses more upon familiarity with places and routes in a neighbourhood. The exact distinction between configurational / survey knowledge and areal / map-like knowledge seems unclear in most of the literature. There does not yet appear to be a clear theoretical basis for separating configurational and areal knowledge, or for relating areal knowledge to the processing of landmark, route and configurational information. However, Aitken and Prosser (1990) argue that areal knowledge provides people with different understanding about the environment from the configurational knowledge. This will be discussed in the next Section.

3.3.2 Spatial knowledge acquisition

People acquire and develop their spatial knowledge through various experiences and processes, which may include recognising and understanding the characteristics of objects, localities, the inter-relationship between elements in environments, and so on.

Shemyakin's Theory (Shemyakin, 1962) suggests that spatial knowledge can be acquired by a process of starting with landmark knowledge, progressing to route knowledge and finally to survey (configurational) knowledge. As knowledge accumulates, so its accuracy in terms of angularity, direction and proximity improves. According to Piaget and Inhelder's development theories (Piaget and Inhelder, 1967), spatial knowledge development progresses over the four phrases of a human life: the sensorimotor period covering infancy, the pre-operational period covering pre-school age, the concrete operational period covering middle childhood and the formal operational period covering the age from adolescence onwards. An individual proceeds from an egocentric pre-representational space, to topological, projective and finally to a Euclidean metric relational structure through these development phrases. Stern and Leiser (1988) further contend that spatial knowledge progresses from landmark knowledge to route knowledge and then to survey (configurational) knowledge through accumulated direct navigation experience and/or map learning at different stages.

Siegel and White (1975) suggest that the process of spatial knowledge acquisition comprises recognising landmarks, finding routes connecting the salient landmarks, and then developing a complex and general configurational survey representation. Thus spatial knowledge acquisition begins with landmarks and develops into route knowledge by the process of joining up the landmarks. This route knowledge progresses from being topological to metric. Groups of landmarks and routes are then organised into clusters based on the metric relationships within them. The topological relationships remained between clusters. In the final stage, a co-ordinating frame of reference develops and thus results in survey (configurational) knowledge. Kuiper (1978) also contends that knowledge of an external environment is hierarchically organised with landmarks, routes and configurations into a coherent structure organised around the relative location of landmarks. The anchorpoint theory of Golledge (1978) is similar, with a hierarchical ordering of locations, paths and areas. He suggests that some locations become primary nodes or anchorpoints from which a skeletal structure develops as spatial knowledge develops outwards from these nodes. Through this spread effect, survey (configurational) knowledge develops.

Over the years, a considerable body of literature (e.g. Kaplan and Kaplan 1982; Thorndyke and Hayes-Roth 1982; Smith *et al.*, 1982; Golledge et al. 1985; Stern and Leiser, 1988) has demonstrated that there is a progression from declarative to procedural and from procedural to configurational knowledge. Using an alternative terminology, there is a progression from landmark to route and from route to survey knowledge. This progression leads to an increasingly complex cognitive representation. Moreover, configurational knowledge of spatial pattern and of spatial relations depends upon integrating landmark and route knowledge into configurational knowledge within some frame of reference. Some studies suggest that route knowledge is acquired by 'chunking' information spatially by splitting routes into segments (Pellegrino *et. al.*, 1987; Gibson *et al.*, 1989). However, Aitken and Prosser's (1990) study suggests that the acquisition of survey (configurational) knowledge is not always sufficient for areal knowledge, as areal knowledge includes propositions and facts in addition to the knowledge necessary to traverse an area. Aitken and Prosser provide evidence that areal knowledge gives individuals better understanding both on cardinal directionality and some non-cardinal features. They argue that knowledge of a complex network may not be enough to provide an areal knowledge structure, and that as a consequence there may be no direct sequential relationship between linear- and areal-based knowledge. They conclude that theories of spatial knowledge acquisition and the relationship between linear knowledge and areal knowledge are still in need of more research despite some weighty studies that have developed some understanding of the transition between landmark and linear knowledge.

Furthermore, Montello (1989) suggests that metric knowledge, such as survey (configurational) knowledge, is acquired and accumulated from the beginning of exposure to the environment. He also contends that non-metric knowledge, such as landmark and route knowledge, is not necessarily a precursor to configurational knowledge and may exist concurrently with metric knowledge. Thus, the non-metric and relatively pure topological knowledge is described as being used in linguistic systems for storing and communicating spatial knowledge about places. Acquiring spatial knowledge in large-scale environments is, therefore, regarded as the quantitative accumulation and consequent refinement of metric information instead of a qualitative change from non-metric to metric knowledge. However, there is some doubt as to the degree to which spatial knowledge is itself qualitative or quantitative (Egenhofer, 1991; Frank, 1992; Mark, 1993).

In the above theories of spatial knowledge acquisition, one has to further consider whether such knowledge is obtained via direct experience or is acquired indirectly. 'Direct' experience is usually taken to refer to that gained through activities in a real environment, while 'indirect' and 'conceptual' experience relates to that gained through assimilating simplified and symbolised representations rather than from exposure to real environments. Direct experience can also refer to active learning modes, in which people view or experience an environment via perceptual focusing, head and body movement (Presson and Hazelrigg, 1984). Indirect experience can be referred to as a passive learning mode, mostly involving only one mode at a time such as vision without direct contact with the environment. From the perspective of spatial knowledge acquisition, direct experiences include route-based learning in a spatial environment and indirect experiences include map study and verbal instructions. Internet or mobile device approaches (such as www.streetmap.co.uk and www.mapquest.com) can be deemed as indirect experiences. Spatial knowledge can also be acquired through VR environments that are structured so as to simulate real environments (see Chapter 4). The indirect experiences referred to in most of the spatial knowledge acquisition literature are experiences of acquiring survey knowledge such as through map reading. Some authors have pointed out that the spatial knowledge acquired in this way is usually assumed to be the most advanced level of spatial knowledge (Shemyakin, 1962; Hart and Moore, 1973).

A number of studies (Thorndyke and Hayes-Roth, 1982; Moeser, 1988; Lloyds, 1989; Giraudo and Pailhous, 1994; Taylor and Tversky, 1996) provide evidence that spatial knowledge acquired through direct experiences provides a better understanding of route distance estimates and route knowledge, while that acquired through indirect experiences (e.g. map learning) facilitate better Euclidean distance and object judgements. In performing object location tasks, people with direct wayfinding experience have to transform route knowledge into survey (configurational) knowledge and complete the task with less accuracy and longer time than those with conceptual map-reading experience. Also, the ability for object location has shown little improvement after repeating the task for those with direct experience. Moreover, for those acquiring spatial knowledge through a map, their verbal descriptions of the environment can be from either a route or survey perspective. On the other hand, those acquiring spatial knowledge through direct wayfinding experience in an environment are more likely to provide route-oriented descriptions. The study by Golledge, Dougherty and Bell (1995) further suggests that people's knowledge acquired via map learning is better than that via direct route learning in understanding spatial relations and suggests that people who are new to an environment will acquire more spatial knowledge if they learn from maps. It is commonly accepted that people acquire better survey (configurational) knowledge through indirect / conceptual experience, particularly through map study, and acquire better route knowledge through direct experience of wayfinding in real environments. However, while Thorndyke and Hayes-Roth (1982) show evidence that reasonably accurate survey knowledge of an environment can be achieved after a long time of repeated direct experiences, Moeser (1988) finds no evidence for accurate survey (configurational) knowledge acquired through direct experience. This raises the question as to whether direct experience invariably leads to survey (configurational) knowledge or whether this outcome depends upon the complexity of the environment.

Another difference existing between the spatial knowledge derived from direct experience and that of indirect experiences concerns orientation specificity effects. Orientation specificity means that the knowledge concerning spatial objects and their layout is strongly associated with a specific orientation. For example, some people who use maps for wayfinding in an environment are likely to associate 'up' on the map with proceeding forward (Shepard and Hurwitz, 1984). Orientation-free, therefore, means that there is no particular orientation attached to people's understanding of their surrounding environment. A number of studies have shown that orientation specificity for map acquired knowledge is a persistent phenomenon (Evans and Pezdek, 1980, Presson and Hazelrigg, 1984; MacEachren, 1992). Evans and Pezdek (1980) also suggest that there is little orientation specificity in the spatial knowledge derived from direct experience.

Pazzaglia and Beni (2001), from a different angle, tested individuals and were able to differentiate between spatial knowledge acquired as isolated landmarks and knowledge acquired from landmarks within route connectivity. They refer to the former as landmark-centred representations, which contain landmarks but lack the routes connecting them. Individuals with landmark-centred and survey-centred representations have different strategies for acquiring and processing spatial information, with survey-centred individuals leading to a spatial-holistic strategy. Their findings also show that landmark-centred individuals made fewer errors than survey-centred individuals in verbal description conditions.

VR experience, as a means of environmental exposure, has some considerable shared common characteristics with direct experience, despite subtle differences. A number of studies provide evidence of connections between direct experience and VR environment experience. For example, spatial knowledge acquired through direct and VR experiences are both shown to be orientation-free when compared with map learning experience (Tlauka and Wilson, 1996). Studies also point out that people who acquire spatial knowledge in virtual reality often have similar capabilities to those who acquire it via direct experience: however, while they can demonstrate extensive and accurate route knowledge, they have less well developed survey knowledge (Witmer *et al.*, 1996; Wilson, 1997; Ruddle *et al.*, 1997). Other studies show evidence that survey knowledge may be acquired more quickly using VR environments. It needs to be noted that the differences amongst various VR systems are likely to provide different levels of realism and active involvement with the environment. This will be discussed in detail in Chapter 4.

Figure 3.2 illustrates the prevailing consensus on the different types of spatial knowledge and their associated characteristics, as summarised from the literature.

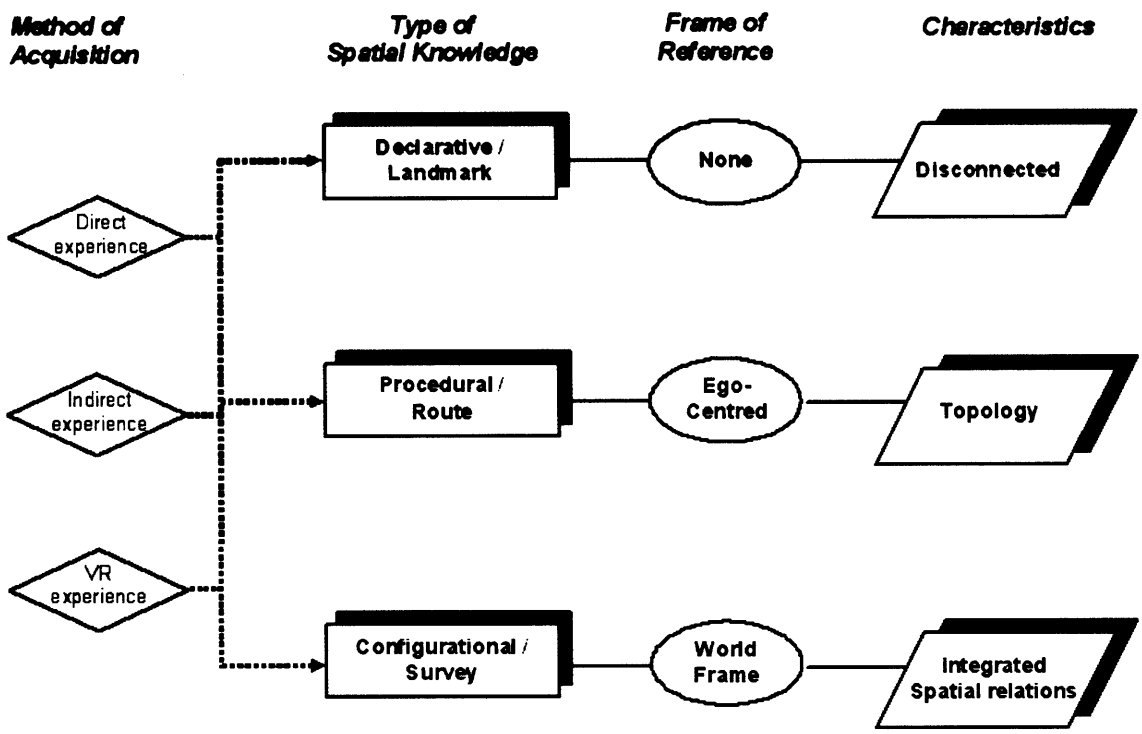


Figure 3.2 An overview of the nature of spatial knowledge, its reference frames and salient characteristics.

3.4 Methods for examining people's spatial ability and spatial knowledge acquisition

A range of tests are widely used in the literature for examining and measuring people's spatial ability and spatial knowledge acquisition (Shepard and Metzler, 1971; Gould, 1975; Thorndyke and Hayes-Roth, 1982; Lloyd, 1989; Silverman and Eals, 1992; Golledge *et al.*, 1995; Montello et al., 1999; Rossano *et al.*, 1999). In this Section, some of the commonly used methods are discussed.

The spatial ability of individuals is often measured from a psychometric perspective (see §3.2.2). Various psychometric tests can be used to indicate an individual's mental ability at handling spatial objects, including mental rotation in three dimensions, orientation, two-dimensional or flat rotation, embedded figures and figural reasoning. One of the examples is the Minnesota Paper Form Board (Likert and Quasha, 1941) which tests participants' decisions as to which of five 2D line-drawings of shapes can be made out of a set of fragmented parts. There are also the Hidden Patterns and Card Rotations developed by French *et al.* (1963), Shepard and Metzler's (1971) Mental Rotation task and the Vandenberg Mental Rotation Test that uses three-dimensional objects (Vandenberg and Kuse 1978).

These tests measure both 'visualisation' and 'orientation' dimensions, static and dynamic spatial ability, two-dimensional and three-dimensional spaces. Previous experience might however influence performance.

A different approach entails the use of questionnaires to provide indications of individual spatial ability, particular with respect to ability in performing spatial tasks in geographic-scale spaces, as discussed in §3.2.2. Questionnaires, often in self-reported styles, can be applied to reveal people's sense of direction, spatial aptitude, spatial preferences and spatial anxieties (Kozlowski and Bryant, 1977; Lorenz & Neisser, 1986; Hegarty *et al.*, 2002). They can also indicate some level of understanding of the individual's spatial thinking (e.g. tend to have landmark or route oriented thinking) and spatial ability (Pazzaglia and Beni, 2001). In addition, questionnaires can be designed to measure people's knowledge about local, national and international places and locations which they know from direct experience or indirect sources such as maps. People's backgrounds, previous knowledge of areas and familiarity in usage of any technologies can be also revealed.

People's knowledge of directions and distances between locations are often measured to indicate how well and accurately people acquire spatial knowledge of an environment. Distance estimation between locations can be achieved through various methods, such as psychophysical ratio scaling, psychophysical interval and ordinal scaling, mapping, reproduction and route choice such as choosing shortest route tasks (Montello, 1991). Direction estimations can be carried out by estimating the direction between two locations in the environment, or by pointing to the direction of one location from another. People are either required to imagine both their location and facing direction in the simulated direction test, or to give directions from within the environment itself in the actual direction test. Distance and direction estimation methods have been used in many forms; however, the validity and reliability of these measurements still needs to be researched (Kitchin and Blades, 2002).

There are various methods for assessing integrated understanding of an environment and the interrelationships between the elements within it. One of these is configuration tests which require participants to arrange objects or locations in the correct spatial relations according to the environment they represent. For instance, people can be required to place a location in relation to others along a route (Thorndyke and Hayes-Roth, 1982). As another example, people are asked to place building objects on a campus plan according to their understanding of the actual arrangement in the real-world (Rossano *et al.*, 1999).

Map sketching is another commonly used method to measure to what degree and what type of spatial knowledge is acquired by people (e.g. Milgram and Jodolet, 1976). It requires participants to sketch routes or maps on paper showing landmark locations, estimated distances, directions, interrelationships and other details after themselves directly undertaking activities in a given environment or gaining indirect conceptual experience of an environment. The content of such measurements can include route reproduction, cue location, distance estimation, orientation and directional tests. The outcome of this method could be influenced by individuals' skill and applied effort in sketching maps.

Completing a wayfinding task in a given environment is another method used in research for assessing people's spatial ability and spatial knowledge gained through experience of the environment. Various tasks are assigned to participants to carry out in real environments, such as walking about and completing tasks in buildings, on campuses and in other environments (e.g. Thorndyke and Hayes-Roth, 1982; Malinowski and Gillespie, 2001). The environment for performing tasks can also be a VR environment, that is, a reality simulated by computer systems. Participants are asked to perform required tasks in these simulated environments (Ruddle *et al.*, 1997; Sandstrom *et al.*, 1998; Steck and Mallot, 2000). Wayfinding performance can be measured by the tasks accomplished (e.g. finding destinations), the time needed and (virtual) distance travelled. The methods discussed in previous paragraphs are also used in conjunction with the wayfinding task performance.

Finally, in order to assess the spatial knowledge gained from map learning, participants may be required to study a map of a given environment and then draw a sketch map including its landmark locations, distances and so on. They may also be asked to provide a verbal description of the route as if they were instructing someone how to follow that route by giving them the most useful information, after having had direct experience of that environment.

3.5 Human-environment interactions

As discussed in the previous Sections, the acquisition of spatial knowledge and performance of spatial tasks such as wayfinding involve interactions between people and their environments.

> "It is commonly agreed in behavioural geography that the acquisition of environmental information, and the use of that information in some form of decision-making process, serves as a prelude to overt or 'acted out' behaviour. In many cases, however, the processing and evaluation of environmental information does not influence overt behaviour and human activities directly. Rather these processes operate to change how

the mind construes the environment, very much in the way proposed in the transactional-constructivist approach to environmental awareness. Thus it is the changed mental construction of the environment that most immediately influences overt behaviour." (Walmsley and Lewis, 1984)

Within the literature there has been considerable research to conceptualize these processes of interaction with the environment and the role of cognitive maps in determining spatial behaviour (Kitchin and Blades, 2002). A wide range of conceptual models have been developed over the years. These have been extensively reviewed by Kitchin (1996) and Kitchin and Blades (2002). This Section does not aim to cover all of these models, but to demonstrate the general concepts embodied in these different conceptual models.

The model established by Kirk (1963) is widely recognised to have introduced the behavioural environment of the decision-maker as separate from the objective environment of the physical world (Figure 3.3). In his model the decision-maker is embedded in a world of physical fact and a world of economic and social facts. The behavioural environment is the basis for rational human behaviour. The behavioural environment is the "psycho-physical field in which phenomenal facts are arranged into patterns or structures and acquire values in cultural contexts" (Kirk, 1963). However, this model has been criticised by its failure to accommodate individual idiosyncrasies.

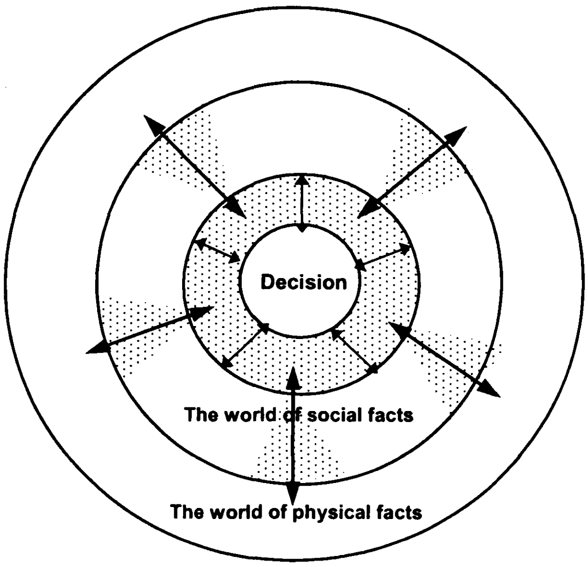


Figure 3.3 Model of behavioural environment of the decision-maker (Source: Kirk, 1963).

Another conceptual model is Downs' (1970) environmental perception and behaviour schema, in which the dynamic process between individuals and environments is emphasised through receiving information and decision-making (Figure 3.4). In this schema individuals derive information about an environment through perception and evaluate this information through their own value system and then arrive at a cognitive image. The cognitive map knowledge is, therefore, continually updated by the flow of new information in order to inform decision-making. The decision might lead to a search for new information from the real-world and start the whole process again until sufficient information has been acquired. Overt behaviour then follows the decision. Although individuals play an important role in this schema, they are still largely regarded as passive receivers and processors of information in the model. Based on Downs' model, Lloyd (1976) and Pacione (1978) add further elements into their models with more emphasis on selecting and processing information by individuals.

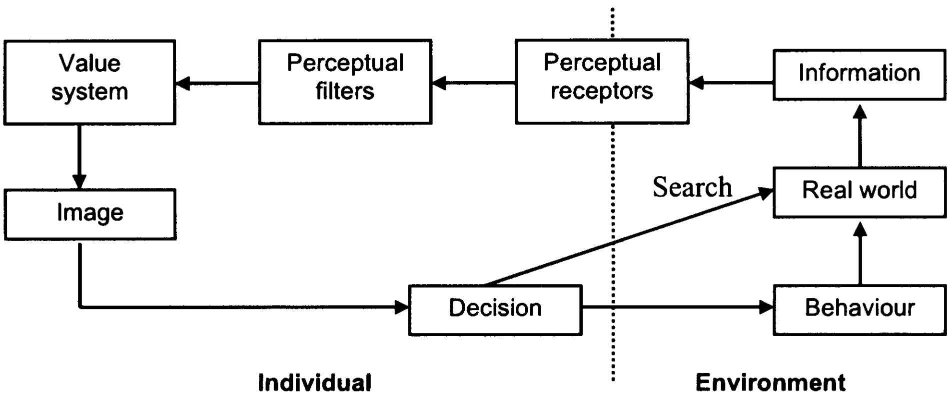


Figure 3.4 Environmental perception and behaviour schema (Source: Downs, 1970).

A more developed model is proposed by Pocock (1973). This model consists of three parts, showing how a perceiver interacts with an environment and processes information to create a cognitive map of that environment (Figure 3.5). The environment includes current context, actual environment and previous information. Individuals' psychological, physiological, and cultural backgrounds interact with their current states in order to determine how they get information from the environment and how it contributes to the development of an environmental image. In this model, individuals are not just regarded as passive receivers but have a more active role in selecting and processing information. Their responses, in this model, also have a feedback on both the environment and the perceiver. Another more complex conceptual framework, developed by Gold (1980) and refined by Golledge and Stimson (1987, 1997), suggests that the individual is part of the objective environment as well as a behavioural environment. Decisions are then made by individuals based on the information received from the behavioural environment.

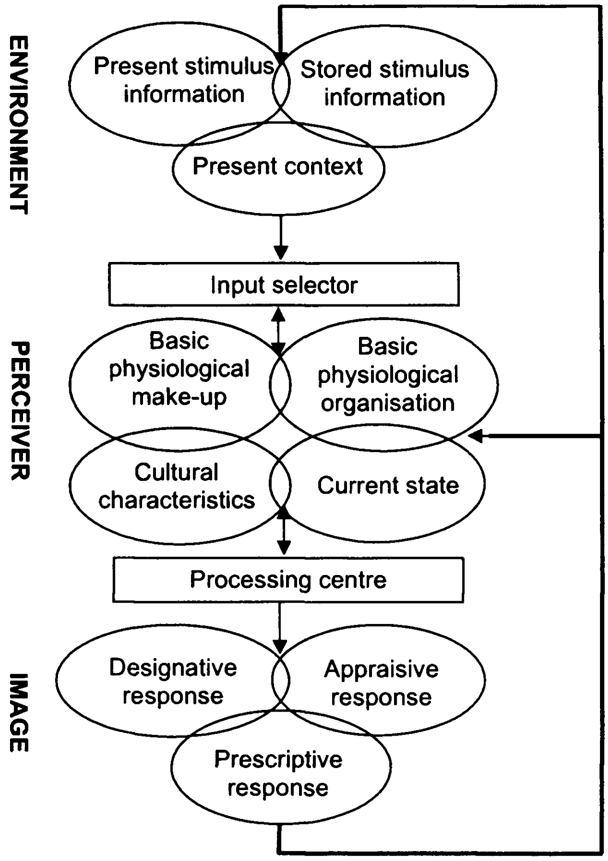


Figure 3.5 Pocock's (1973) model for interactions between environment and individuals.

Different from the sequential models above, Neisser (1976) proposes a schema with an active information-seeking structure (Figure 3.6). In this schema all elements are synchronous rather than temporally successive. Individuals actively and selectively search the environment to gain information. In other words, individuals select the relevant information discriminately and actively for their needs. Furthermore, one schema can be embedded within another, and several of them can be active simultaneously in a cyclic interaction with the environment.

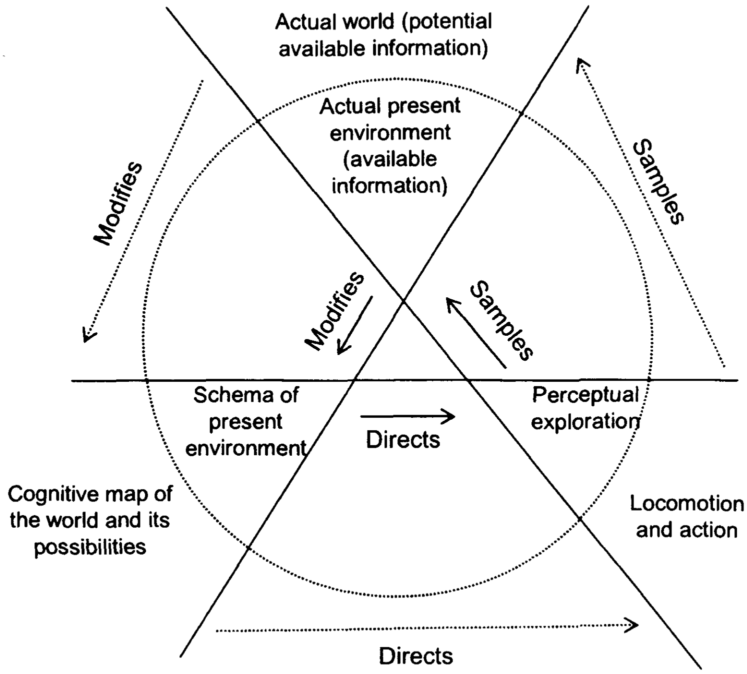


Figure 3.6 A schema for individuals interacting with the environment (Source: Neisser, 1976).

An integrated conceptual schema is proposed by Kitchin (1996), which comprises three sections as illustrated in Figure 3.7. The first section, the 'real-world' section, is the environment acting as primary environmental interaction sources and secondary social interaction sources. Individuals interact with this environment which influences the development of the cognitive map and individuals' spatial decisions. The 'working memory' section represents the effect of personality and character upon the process of conscious and unconscious thinking, and includes senses filters and such factors as beliefs, needs, emotions, values, personality, preferences and desires, all of which will influence any decisions made. The third section, 'long term memory', illustrates how our knowledge is stored and accessed in the memory, which contains an events store and an information store. All sections in the model are embedded rather than successive, and the whole system is dynamic.

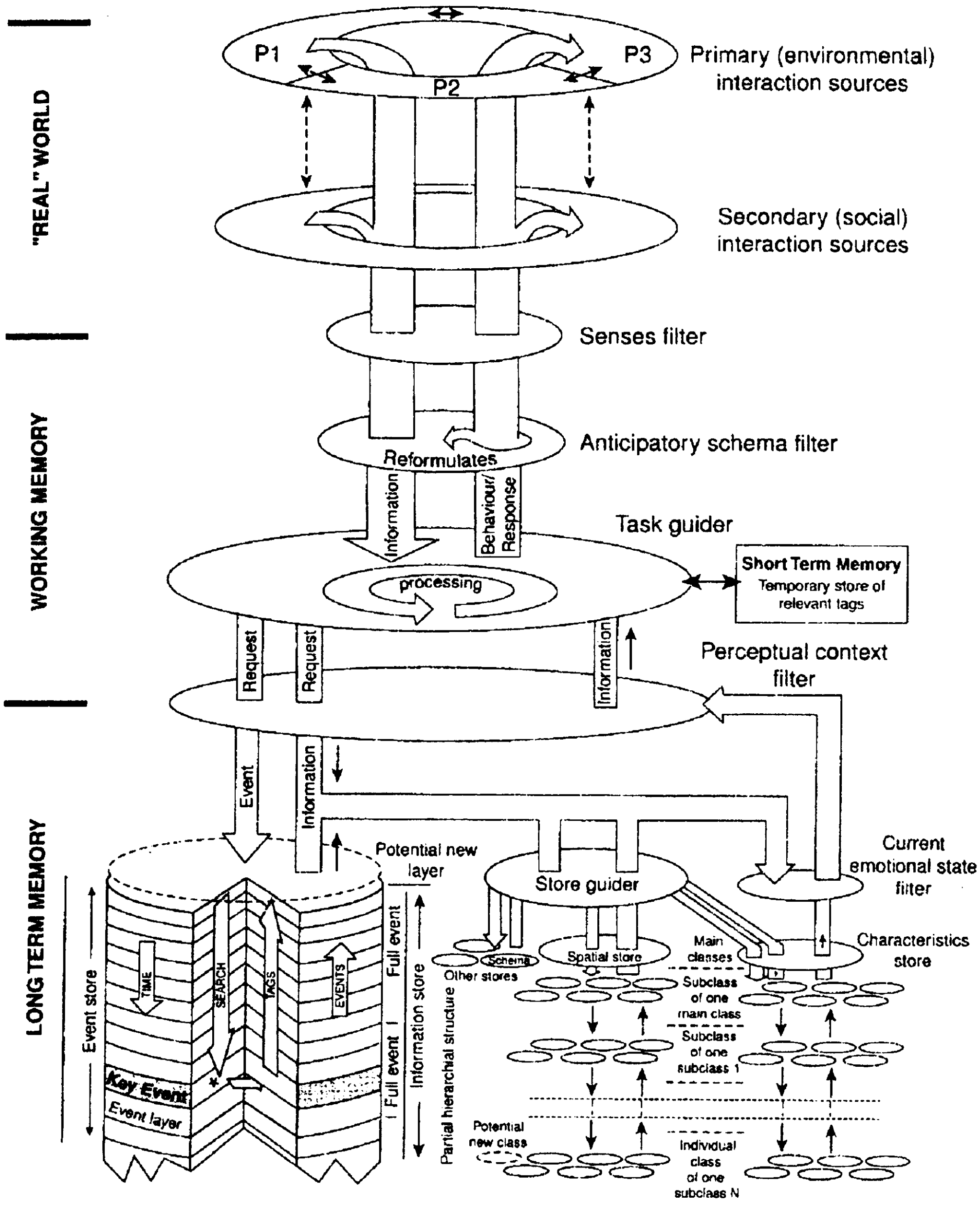


Figure 3.7 A conceptual schema by Kitchin (1996).

As pointed out by Kitchin and Blades (2002), many such conceptual models "have not always generated much empirical research". Many of these models also have a strong emphasis on "people's thought, knowledge and decisions which influenced that behaviour, rather than by studying the behaviour itself" (Golledge and Rushton, 1984).

3.6 GIScience and spatial information

Geographic Information Science (GIScience) is pertinent to the discussion in this Chapter from two perspectives. Firstly, the individual is increasingly at the heart of GIScience and therefore an understanding of individual cognitive processes in understanding spatial concepts and reasoning with geographical data is important (Longley et *al.* 2005). Secondly, as discussed in §2.3.4, mobile technologies are transforming the ways in which geographical information (GI) can be accessed and used in real-time whilst on the move and hence it is becoming more intimately connected with environmental contexts and individual decision-making. In applications such as LBS, this looks set to have implications for human-environment interactions during wayfinding.

Goodchild (1990, 1992) argued that the systematic study of geographical information constituted a scientific domain. He set forward two main criteria for the recognition of this science: that there were a legitimate set of scientific questions and that spatial data were unique. Thus the spatial key {x, y}, the presence of spatial dependence (Tobler's First Law of Geography) and the durability of the spatial data primitives of point, line, polygon and cell/pixel (Burrough, 2000) creates a well-defined class of information in its own right. In this view, geographical information systems (GIS) provide tools for geographical information science. Whereas Information Science studies the fundamental issues arising from the creation, handling, storage, and use of information, so GIScience studies fundamental questions for the creation, handling, storage, and use of geographical information (Longley et *al.* 2005). Mark (2003) also lists key research themes of GIScience as including data structures, algorithms, data quality, spatial analysis, visualisation, ontology, spatial reasoning, and cognition including human-computer interaction.

Mark (1999) has expressed a cognitive view of GIScience. It is assumed in any computational (digital) system, that the data (entities) and processes (algorithms) have some correspondence with and meaning in the real world. 'Representation' and the fidelity of representation are key factors in usability. Representations of geographical things rely to a greater or lesser extent on our cognitive perspective of the real world and are therefore an important issue in GIScience. Some aspects of the geographical world can be determined objectively through measurement; while others rely more heavily on perception, reasoning and memory. Thus an object, such as place of worship, can take many forms (church, mosque, synagogue) which each need to provide cues that make them recognisable as places of worship. Once recognised and so classed their location and extent can be determined objectively using GPS, aerial imagery and/or land surveying. The reverse process from digital representation must also be possible for the digitisation of places of worship to have any use. The ontology of geographical space determines what things are deemed to exist and also necessitates the use of language. Language is a specialised form of behaviour and can be a means of communicating thought. Thus we can differentiate basic geographical entities such as 'point', 'line', 'polygon' and 'cell' using linguistic terms for which there are very specific meanings. The classification of things according to accepted ontologies is a fundamental cognitive process. We tend to view geographical objects as categories of things (road, hill, town). This can also be extended to spatial relations between geographical objects such as 'north of ', 'near' or 'within'.

> "Nothing can be more abstract than, more unreal than what we actually see. We know that all that we can see of the objective world, as human beings, never really exists as we understand it. Matter exists, of course, but has no intrinsic meaning of its own, such as the meanings that we attach to it. Only we can know that a cup is a cup, that a tree is a tree." (Giorgio Morandi, artist, 1890-1964)

Goodchild (2003) considers that digital information has the advantage that it can be changed into other forms through transformations. GIS make it easy to carry out such transformations for spatial information. He further proposes that rather than measuring 'quantity' of information in terms of, say, bytes, it would be better to base such a measure using semantics, in other words, to focus on the meaning of the information (semantics) rather than its form (syntax) or file size. Such a measure also needs to distinguish between information which adds knowledge to a user as separate from that which only duplicates existing knowledge. Frank (2003) extends this discussion to consider 'pragmatic' information content in the context of wayfinding. In doing so he suggests "a formal approach to relate data to the practical situation in which it becomes information". He defines the pragmatic information content as being a measure of the amount of information useful for decision-making. In his schema, information is received by an individual and is used for decision-making as expressed in the individual's overt action. However, from the discussion of §2.3.4 and §3.5 we need to extend this schema to include the nature of the initial request for information by the user, say, using a mobile device, and how the server-side GIS might interpret the request and respond in relation to the data sets that are available. What information is requested and the actual decision/overt action taken are likely to depend on the nature of the problem/task facing the individual on the move, the nature of the surrounding environment and the immediate context of the situation (e.g. day/night, sunny/raining). Hence, the introduction of mobile devices and the access to spatial information in real-time and whilst on the move, poses fundamental questions for GIScience.

3.7 Conclusion

This Chapter has reviewed the research literature on spatial acuity, spatial knowledge acquisition, human-environment interaction and cognitive aspects of GIScience. These are all closely interconnected when considering wayfinding activities in the presence of mobile information devices. However, there is a lack of research into the interactions and spatial information transactions between individual, environment and their mobile device. This research focuses on developing an understanding of these interactions and spatial information transactions. The methodology is developed in Chapter 5, but before doing so it is necessary to consider the validity of using virtual reality as a test environment to study such interactions and transactions. This forms the subject matter of Chapter 4.

CHAPTER FOUR
Virtual Reality

Virtual reality (VR), as a research domain, involves in a number of disciplines including computer science, psychology, planning, architecture and geography. In some of these disciplines, VR is becoming an indispensable tool. The purpose of this Chapter is to review some issues which are related to using VR in this research. In §4.1 the definition and components of VR are presented and different types of commonly used systems are described. In §4.2 issues of realism and presence are discussed. §4.3 presents a review of research on acquiring and learning spatial knowledge through VR in comparison with the real world experiences. The conclusions in §4.4 highlight the applicability of VR as an environment for studying and understanding human spatial cognition in the real world.

4.1 Virtual reality

The definition of virtual reality has been expressed differently by a number of authors. Virtual Reality (VR) or Virtual Environment (VE), in a literal sense, provides three-dimensional representations of computer generated objects projected to two-dimensional displays, within which people view and interact (Slater *et al.*, 2002). One common characteristic of VR is that it is not just the flat screen which people look at, but is a three dimensional visual world in which people feel a degree of immersion (Lathrop, 1999). VR is also referred to as virtual environments or virtual worlds (Batty *et al.*, 1998). In this thesis, the term 'virtual reality' (VR) is used. There are three major components that constitute virtual reality, as suggested by Ellis (1991). They are content, geometry and dynamics. The content is a set of objects forming the virtual reality, whilst the geometry comprises dimension and extent. The dynamics of the virtual reality consists of the interaction rules between the objects. VR can also be defined and used according to the emphasis of different research domains. Thus, VR research can be classified according to its emphasis upon different research foci of visualisation and data modelling (Fisher & Unwin, 2000) and upon its substantive domain of application (specifically urban versus rural: see Lovett 2005). Batty *et al.* (2002) provide a time line showing the development of virtual environment with virtual built environments context (Figure 4.1).

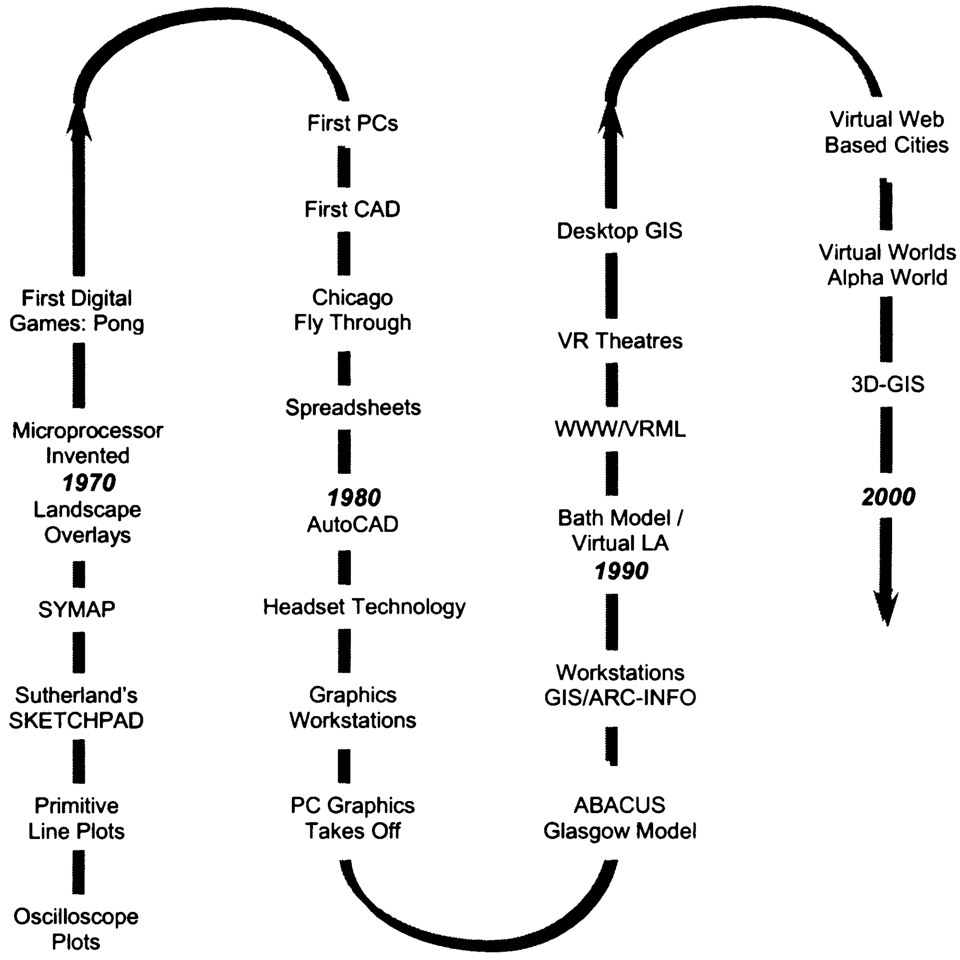


Figure 4.1 The development of virtual built environments: A time line
(From Batty *et al.*, 2002)

There is a range of VR systems employed in various applications, from non-immersive desktop display to immersive CAVE systems. Here some commonly used systems are discussed, which by no means includes all the VR systems. For desktop VR systems, virtual environments are viewed through a standard desktop monitor. Normally mice, joysticks, trackballs and keyboards are used for interacting with the VR environment displayed on the monitor. Such systems are non-immersive and provide only a limited field of view. However they can be implemented on most computers with different levels of graphics performance. Another type of VR system is implemented using a large screen projection system and a relatively high performance graphics computing system. In some of these systems, shutter glasses are used for stereographic images. A range of devices is used for interacting within the VR environments such as joysticks. This type of VR system provides some level of immersion compared with desktop VR systems, but is not regarded as fully immersive. Head Mounted Display (HMD) VR systems can be regarded as immersive. HMDs use a small screen (LCD – Liquid Crystal Display or CRT – Cathode Ray Tubes) in front each eye to provide stereo views. User head movements can be tracked through a device located in the HMD system. The system updates the VR display continuously according to the head movement and constructs views taken from changing perspectives. User views of the real world are partially or completely blocked, and what is seen is the wider field of view provided in the VR environment. Therefore, users feel greater immersion in such VR environments. More powerful computer systems are always needed in order to achieve higher levels of realism with acceptable fields of view. Moreover, HMD equipment is heavy on the head. Similar to HMD, Binocular Omni Orientation Monitor (BOOM) VR systems can be viewed as immersive. In these types of VR systems, there are two lenses in BOOM's viewing box. Users put their foreheads against the box in order to view the display. Handles, control buttons or other devices can be used to interact with the VR environment such as to move around. Cave Automatic Virtual Environment (CAVE) systems are regarded as immersive VR systems (Cruz-Neira *et al.*, 1993). In a CAVE, the images are projected onto the walls and floor. These projected images achieve a stereo effect by rapidly alternation between the two eye images. A person with shutter glasses in the room can see a 3-D effect view. Track devices may be used to feed back changing locations and head movements to the computer system for updating the display continuously. Users can look in different directions and 'move' through the environment by using joysticks, treadmills and other devices. Any real world objects located in the room can also be seen through the user's shutter glasses.

4.2 The realism of VR and the sense of presence

It is extremely difficult to create 'reality' in a computer projection display; VR aims to provide a sufficiently realistic display for people to accept an illusion of being in a form of reality. Slater *et al.* (2002) discuss the realism of VR from several computer graphics meanings: geometric visual realism, illumination realism and behavioural realism. Geometric visual realism concerns the closeness of geometrical resemblances between graphical objects in VR and corresponding objects in the real world. For example, a building needs to have walls, windows and doors in the dimension corresponding to a building in the real world if such a real world building is to be represented in VR. Illumination realism is about correct lighting of objects and scenes, which can be more important in some applications such as representing day- and night-time scenarios. Behavioural realism concerns the behaviour of objects in VR which give observers a sense of realism despite a paucity of geometric and illumination realism. Taking the research results from Pertaub *et al.* (2002) as an example, participants with a phobia of speaking in public were placed in front of a virtual audience. The participants experienced different levels of anxiety when the virtual audience showed different expressions and movements consistent with interest or boredom although it was obvious to the participants that such an audience was not geometrically real. Although realism is often the aim of computer graphics, in fact the results are often highly iconic and impressionistic.

More importantly, real-time performance in VR is essential (Slater, *et al.*, 2002). The real-time performance in VR, in general, means that the correct sequence of many images are displayed with a speed fast enough for people to see a continuous scene. Moreover, in VR, this display must also correspond with the actions and interventions of the people within the VR. Interaction with objects in real-time in VR is one situation requiring real-time performance. Yet another situation, which is particularly related to this research, is real-time walk-through in VR. In a real-time walk-through situation, a person can move about in a VR setting and look around without experiencing noticeable delay of images. For example, when walking down a street, a person might be able to move along the street and look around the buildings on the either sides of the street. When he/she looks left or right, the physical movement of head is tracked with feedback to the computer system. The system continuously updates the image display within an acceptable time delay in order to present the kind of smooth moving view that one would experience when moving one's head around. Likewise, when looking down the street, a view of a row of buildings would be seen, although the more images that need to be rendered by the system, the longer the refresh interval. The ideal image updating rate should be at least 60Hz, i.e. 60 images per second (also called the frame rate) (Slater *et al.*, 2002). Lower frame rates would give a jerky appearance which may cause 'motion sickness'. Therefore, given the computer power, there is a balance (or tension) between degree of realism and real-time performance. The level of detail of objects can be reduced in order to improve the real-time performance. There are also approaches that create different levels of detail for objects from different view locations (Cote, 2005). For instance, near objects will have more realistic displays than those further away. However, there are few studies and guidelines available on the level of acceptable detail with respect to viewing distance, with consideration to realism and real-time performance. Furthermore, the changing of detail is a more of a fuzzy process than a clear cut distance-related variable from a human perspective.

A particular aspect of VR research, which is relevant to this research, has been the notion of 'presence' in a virtual environment. Presence in VR means the concept that participants experience a 'sense of being there' within the environments created by VR systems (Held and Durlach, 1992; Sheridan, 1992). The issue of sense of presence is a common thread in most VR applications because it is believed likely to be associated with behaviour in VR environments and has a close link with the effectiveness of VR usage. There are two different aspects to the sense of presence. One of them considers sense of presence as "a mental state in which a user feels physically present within the computer-mediated environment" (Draper *et al.*, 1998). People experiencing VR have a sense of being in the environment created by the VR technology instead of in the actual environment where they are physically located. Another view on presence considers that it is not just the pure mental state but the actions in the environment that form the reality of the experience (Zahoric and Jenison, 1998). The action one undertakes in the VR is considered more important than just the appearance of the VR. From this perspective, sense of presence is fundamentally about a user's ability to do things. Furthermore, a distinction has been drawn between the concepts of 'presence' and 'immersion' (Draper *et al.*, 1998; Bystrom *et al.*, 1999), and there is a sense in which level of immersion has an effect on the degree of presence in a VR environment (Sheridan, 1992; Witmer and Singer, 1998)

Studies have been carried out on the sense of presence in VR environments. The sense of presence in VR is a multifaceted concept, and therefore has been studied from a number of aspects. The comparison between the experience in VR and the real-world has been studied. For example, in a study by Usoh *et al.* (2000), there were two groups of participants. One group carried out a task in a real site and another group performed the same task in a simulated VR of the same site. The questionnaire results identified the overall similar levels of presence between participants in VR and in real site experiments. Various factors in VR which contribute to the sense of presence have been studied and indicate that the involvement and control in VR contribute to a strong sense of presence (Witmer and Singer, 1998). Involvement in VR concerns focusing one's attention on meaningful activities, events and/or stimuli, and where control concerns the interaction with environments. Studies into the relation between body movement and presence have also been carried out. For example, a positive association between movement and presence was shown for people who actively interacted in the VR. This was shown by using questionnaires and measuring the number of transitions between the reported state in the VR and in the real world (Slater and Steed, 2000). In other studies, level of measurable anxiety is shown in some stressful VR environments through physiological measures to indicate a sense of presence (Rothbaum *et al.*, 1995; Meehan *et al.*, 2002). Moreover, people's responses to virtual motion stimuli in VR environments (e.g. flying objects) have been demonstrated, thus showing a sense of presence in VR situations (Freeman *et al.*, 2000). Sense of presence questionnaires of people's experience in VR do indicate that presence can be measured by these instruments. However, this method has been questioned because of the ethereal nature of 'presence' and the ways in which participants interpret such questions (such as the feeling of 'presence'). Thus Slater (2004) has suggested the use of a combination of methods, rather than heavy reliance upon questionnaires. In general though, studies show a common agreement on the sense of presence in VR and support the view that VR triggers a similar perception and set of behaviours as in reality.

4.3 Spatial learning through VR

VR technology has been used in a number of areas: tools to visualise and interact in situations and structures which cannot be seen or are difficult to manipulate directly by humans; training programmes in different scenarios; augmented reality which combines real world and virtual world; distributed collaboration of people at different geographical locations; entertainment such as computer games. In many VR technology applications, the knowledge gained from VR has been considered to be similar to that learned from the real-world. However, some differences might be expected to exist between knowledge acquired through experiencing the real-world and experiencing the environments created by various VR systems. Research has been carried out from different aspects on the knowledge gained from the experiences in VR environments.

As discussed in Chapter 3, spatial knowledge can be acquired and gained through direct and/or indirect experience. Direct experience refers to the activities in a real environment such as viewing or experiencing an environment by interacting with the real-world, while indirect experience relates to that gained through simplified and symbolised representation without direct contact with the environment – as, for example, when gaining knowledge of a spatial layout through reading maps. VR experience, as a means of environmental exposure, shares many characteristics with direct experience, despite subtle differences. The sense of presence in VR, as discussed in §4.2, also contributes to the experience of being in a real geographically extensive environment. A number of studies give evidence for a connection between direct experience and VR experience. VR environments could be regarded as primary sources for spatial information instead of secondary sources (Liben, 1997; Wilson, 1997). In general, VR environments simulate real environments in an iconic representation instead of using the kinds of abstract symbols used in conventional mapping. As such, VR environments provide a more natural source for acquiring and learning spatial information than learning from a symbolically-presented pace. Therefore, people acquire spatial information in VR environments with less cognitive effort than that required by maps (Hunt and Waller, 1999). In Rohrmann and Bishop's (2002) studies, a VR walk-through urban environment with man-made feature and natural features was created in several variations (such as day/night, sunny/foggy, sound/no sound and shadow/no shadow) for investigating responses on validity of computer simulated environments. The findings from the responses on appraisals of relevant environmental attributes, perceived quality of VR environments, comprehension and retention showed that such simulated environments were generally acceptable as valid representations of environmental features. The potential of using VR environments for studying human behaviour is evident (van Veen, et *al.*, 1998; Bishop, et *al.*, 2001). However, different aspects and forms of VR might not simulate exact direct experience in the real-world.

Another aspect studied is the orientation-specificity of spatial knowledge acquired through direct and VR experience. Orientation-specific spatial knowledge has preference for a particular orientation. Orientation-specificity is one of the main characteristics of map acquired spatial knowledge, whilst knowledge learnt from direct experience shows little such orientation-specificity. For the VR experience, some studies show that spatial knowledge acquired through VR experience has no orientation-specificity, that is, knowledge similar to that acquired through direct experience (May et al. 1995; Tlauka and Wilson, 1996). However, the evidence of orientation-specificity in experiencing computer simulated environments was found in some studies such as the one carried out by Rossano et *al.* (1999). Nevertheless, it should be noted that the VR environments, in this experiment, were presented to participants in an experimental setting, instead of participants exploring the VR environment. Rossano and Moak (1998) found that when free exploration was allowed, orientation-specificity was weakened.

Studies also point out that people who acquire spatial knowledge in VR often have similar capabilities to those who acquire their knowledge via direct experience and can produce extensive and accurate route knowledge but less well developed configurational knowledge (Witmer et *al.*, 1996; Wilson, 1997; Ruddle et *al.*, 1997). Other studies provide evidence that survey knowledge may be acquired more quickly using computer models. The study by Rossano et *al.* (1999) with regard to spatial knowledge acquired using computer models, showed some tendency towards a better performance compared with map learning for route knowledge and poorer performance for survey knowledge. The degree to which survey knowledge can be acquired through VR experience is not clear. This could be the fact that surveying knowledge is difficult to acquire through direct experience in the real world. Thus the experiences in simulated VR environments, which similar to direct experiences, have the same effect. Nevertheless, the study suggested that both route and survey knowledge can be acquired through VR experience. It should be noted, however, that some experiments carried out in this study were performed passively rather than with active movement. This could have had an impact on the results of acquisition of spatial knowledge.

That spatial information is acquired through VR and in a similar manner to the real world is further confirmed by a number of studies that have been carried out on specific aspects of wayfinding and spatial learning in VR environments (Darken & Sibert, 1996; Sandstrom *et al.*, 1998; Murray, 2000; Ruddle & Peruch, 2004). For example, Sandstrom *et al.* (1998) studied gender differences in wayfinding using a VR environment. Steck and Mallot (2000) investigated the role of global and local landmarks in completing wayfinding tasks by altering landmarks in VR environments. Furthermore, the use of navigational aids whilst in VR can improve spatial knowledge acquisition and wayfinding performance (Schlender *et al.* 2000; Witmer *et al.* 2002). In general, VR environments can be considered to provide acceptable and valid representations of environments for most participants and can be used as an approach to study human behaviour and human-environment relations.

4.4 Conclusion

In the above Sections, a number of arguments have been put forward concerning the validity of using VR as a simulation environment that allows the study of spatial cognition and learning as if in the real world (Loomis *et al.* 1999; Wilson, 1997; Montello *et al.*, 2004). As discussed, there are several important facets to this issue such as orientation specificity, acquisition of route and survey knowledge and wayfinding performance. The general consensus is that VR experience and direct experience of the real world share many salient characteristics and that VR can be used in studies of human behaviour.

Questions still remain concerning some aspects of VR that might not provide an accurate simulation of direct experience, particularly the issues of whole-body movement, control of locomotion and extent of field of view (Montello *et al.*, 2004) Nevertheless, research has shown that spatial cognition and the acquisition of spatial information can be studied effectively using VR simulated environments. Different types of VR systems used vary, which can affect the experience and learning of spatial knowledge. As discussed in §4.1, different VR systems do give different scales of field of view, different levels of immersion and interaction with environments. Activities and interaction with VR environments provide a more direct experience than passive viewing of the environment. Another important aspect, which is often overlooked, is the type of VR environments created for studies. The types of environments (e.g. inside buildings or rooms, campus, streets) and complexity of environments created (e.g. different spatial layout, buildings and objects in environments) would have an influence the degree of similarity between experience in VR and the real world.

VR has certain advantages from a research perspective. Firstly, the VR environment can be purpose-built to contain all the features that may be relevant to the research. Secondly, it can offer a consistent environment over which there is a high level of control yet allowing an equally high level of user interaction (further discussed in Chapter 5). Thirdly, it is possible to track the movement and monitor overt behaviour within the VR environment so that repeated experiments can be compared.

A CAVE VR system is used for this research. As discussed in §4.1, there are different levels of immersion available through a range of VR systems. Taking into account the level of immersion of the system and the feasibility of using real-world mobile devices in a virtual environment, large screen projection VR systems and CAVE systems were considered initially in this research. In CAVE systems, a wider field of view and a relatively realistic change of view with head movement can be obtained. Moreover, in a CAVE system, the technology can accurately track the movement of the individual within the virtual environment. As will be discussed in Chapter 6 the realism of the images and the geometric fidelity of the objects usually require some level of trade-off in order to achieve a smooth real-time performance. The overall goal is to create a VR environment that provides a high level of presence so that individuals can have a matching experience as if in the real world, particularly their wayfinding strategies.

CHAPTER FIVE
Conceptual Model and Methodology

As discussed in Chapter 2, the rapid development of mobile telecommunication technologies and the foreseeable usage of LBS applications pose new challenges and research questions for geographical information science and research into wayfinding. On the other hand, while the changing aspects of new technologies can enable researchers to explore different approaches, such as how a mobile device can be used for assisting people's wayfinding, they can also be used to collect data on the way in which people use spatial information (which will be discussed in this Chapter). Virtual reality, as discussed in Chapter 4, is used in this research for overcoming some of the methodological challenges for studying individual interactions with mobile technologies and environments in real-time. The extensive literature reviewed in Chapter 3, has identified the lack of research into the technological dimension to the interaction of individuals with their environments; to date there has been little research that explicitly focuses on the real-time interactions and spatial information transactions. Therefore, in this Chapter, a conceptual model is proposed which brings into focus the interaction and spatial information transactions between three main elements: individuals, mobile devices and environments. Challenges in studying such interactions and information transactions will be discussed and a novel methodological approach which has been developed for this study is presented. The details of implementation will be discussed in Chapter 6.

5.1 An interactive conceptual model

As discussed in Chapter 3, there has been considerable research into the processes of human-environment interaction, and in particular the role of spatial cognition, that is, the acquisition, storage and use of spatial knowledge in determining spatial behaviour. Since the 1960s there have been numerous conceptual models which have sought to embody theoretical understandings of the processes of such interactions in geographical space. These models have evolved considerably in their remit and complexity. Yet the principal focus has remained fixed upon two main elements: human beings and their innate qualities, and the environment as perceived and socially constructed. However, modern information and communication technologies increasingly act as a mediator between humans and their environments. Consequently there is a fundamental need to include this new aspect into the research. Moreover, given the short-term dynamics of many interactions there is a need to study and understand real-time processes which in turn necessitates being able to capture the actual dynamics taking place in real time.

Considering further the technological element, as discussed in Chapter 2, one of the main applications of fast developing mobile technologies is LBS, that is, the provision of location aware and context aware information which can be used to assist people in various wayfinding activities. Many applications aim to deliver spatial and spatially-related information to individuals who increasingly require more relevant and timely information via their mobile devices in order to perform various tasks. This shift from generic to user-centred mapping is one of the important challenges currently facing geographic information science (Longley *et al.*, 2001, Chapter 21). A related challenge concerns people's use of mobile technologies to access spatial information for their spatial activities in real-time, at any location. For example, in the applications of LBS that entail navigation, instructions could be given to people by means of maps, spoken word and/or text. It is envisaged that landmarks, points of interest and key features of neighbourhood environments will be provided as spatial cues via LBS. Yet there has been little research into understanding the way in which such spatial information services, via a mobile device in real-time, might be used at group- and individual-levels. Whilst interactivity between a mobile computing device and its user has been studied, the focus has been on the usability of devices with a clear emphasis on the design and implementation of systems with evaluation in laboratory settings. In such studies the surrounding environment is under-represented with limited attempt to accommodate the spatial environment on the interactions studied (§2.3.2). Few studies have explicitly focused on the dynamic interaction between individuals, mobile technologies and their surrounding environments.

In this research, a conceptual interaction model is proposed, bringing together the individual, mobile devices and environments as three elements and putting the focus explicitly on the interaction and spatial information transactions between them (Figure 5.1). Individuals, as one of the elements of the model, can access and acquire spatial information through a mobile device whilst acting and moving within the environment. They can also gain information directly from the environment. Individuals have been shown to have differences in terms of spatial ability, acquired knowledge and their social and cultural backgrounds. Mobile devices, as the technological element, act as information sources. In LBS applications, the mobile device is the medium by which information and services, tailored to the current or some projected location within the environment, are delivered to the individual. The environmental element can be viewed as including physical, socio-economic and cultural aspects (Gollege and Stimson, 1997, also seen Figure 3.1). The environment in which individuals act also identifies both spatial extent and context in terms of the various situations encountered.

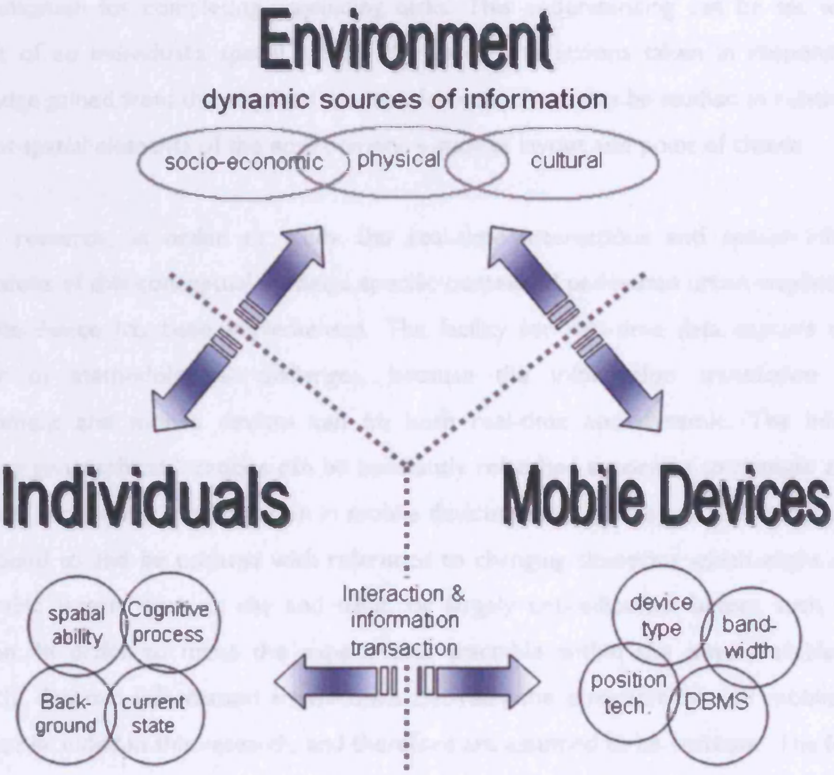


Figure 5.1 The proposed dynamic interaction model.

This dynamic interaction model explicitly places an emphasis upon overt interactions between individuals, environments and mobile technologies, and focuses on spatial information transactions. Rather than considering the complex cognitive processes carried out internally when individuals encounter environments, this conceptual model takes a different approach to investigate real-time, overt interaction. Instead of looking at individual elements or individually paired interactions, the model proposes that all three elements and their interactions need to be considered in their totality. Furthermore, in order to reach an appropriate level of understanding, the model requires real-time interactions and spatial information transactions to be studied. Taking the scenario of completing wayfinding tasks, individuals gain information about the environment from its distinctive physical features and on-going activities. The environment itself can be a dynamic source of information. When individuals are on the move, the information delivered via LBS-enabled mobile devices can be updated depending on their specific location. Individuals can request information through their mobile device at any time they require assistance in completing their wayfinding task.

Thus by studying the details of these interactions and spatial information transactions, we can gain an understanding and insight into the level of information that is sufficient to individual needs, the desired types of information, frequency of use and preferred modes of communication for completing wayfinding tasks. This understanding can be set within the context of an individual's spatial ability. Moreover, the actions taken in response to the knowledge gained from the acquired spatial information can also be studied in relation to the different spatial elements of the environment – such as layout and point of choice.

In this research, in order to study the real-time interactions and spatial information transactions of this conceptual model, a specific context of pedestrian urban wayfinding using a mobile device has been implemented. The facility for real-time data capture creates a number of methodological challenges, because the information transaction between environment and mobile devices can be both real-time and dynamic. The information regarding geographical locations can be constantly refreshed according to changes at specific locations. Furthermore, information in mobile devices such as maps and instructions can also correspond to and be updated with reference to changing situations which might either be predictable factors such as day and night, or largely unpredictable factors such as traffic situation. In order to make the experiments tractable within the time available for the research, dynamic information transactions between the environment and mobile devices were not included in this research, and therefore are assumed to be constant. The focus was therefore on studying the real-time interactions and spatial information transactions between the individual, the environment and their mobile device.

5.2 Methodology

There has been a range of methods established and adopted to measure individual spatial ability, studying how people acquire spatial information and develop spatial knowledge. These are often used to understand people's inner representation of the environment, which is regarded as an important aspect of wayfinding research. As discussed in Chapter 3, these methods include:

- Self-reporting (self-rating) questionnaires.
- Tasks based on estimating distance and direction (in order to measure people's spatial knowledge of locations) using various methods of measurement. Usually these are uni-dimensional, measuring a single element rather than the whole configuration of an area. Although the single elements can be combined to measure the whole, the knowledge gained is constructed afterwards.

- Sketch maps drawn of an area in order to understand people's configurational knowledge about the area and of the locations of objects in relation to each other.
- Completing tasks such as retracing a route, remembering landmarks and routes taken.

These methods are generally used to investigate people's cognitive mapping aspects of wayfinding. However, there are issues of validity and reliability of these measures, as little research has been carried out to assess them (Kitchin and Blades, 2002). Furthermore, such data and measurements taken in a static situation after actually carrying out spatial tasks are likely to be influenced by a number of confounding factors such as different levels of individual knowledge and skills to perform such techniques, the ability to remember, willingness/patience to complete the measurement tasks and *ex post facto* rationale. However, the challenge of capturing the actual process in real-time still remains, since although it is possible to measure various manifestations of spatial knowledge and to measure aspects of how people acquire and learn spatial information, many of these methods attempt measurement after the activities of the wayfinding tasks have ceased. Apart from the obvious difficulty of making measurements in dynamic, mobile situations, there is also the issue of the extent to which spatial information has practical use (Frank, 2003).

As discussed in the previous Section, the proposed conceptual model focuses on exploring interactions and spatial information transactions between individuals, mobile devices and environments (Figure 5.1). The approach for implementing such a conceptual model put its emphasis upon gaining insight into the actual process. There are, however, a number of implementation challenges. To begin with, a real-world environment usually encompasses a larger geographical area for movement compared with a laboratory- or desktop-based situation. A real-world environment is difficult to control and can easily confound different aspects of user behaviour and interactions. For example, a real urban environment may vary during the time period that experiments are being conducted, in terms of weather conditions, seasonality of vegetation, busyness and so forth. Thus the seemingly infinite complexity of the real world is likely to provide interrupting and disrupting stimuli that become a challenge in the conduct of controlled studies. In addition, the information provided through mobile devices should be available on demand for assisting individuals to complete tasks. However, such applications are not yet widely used and it may be difficult for some individuals to understand their usefulness in relation to a full range of personal information requirements. There are also practical issues of safety and the ethics of carrying out experiments in the street with traffic and other hazards. Thus many, current methods have severe limitations and present difficulties for capturing interactive behavioural data pertaining to spatial information transactions by mobile individuals.

In this research, a different methodological approach has been established and implemented, with the focus on collecting and analysing data from real-time information transactions and overt interaction behaviour. The approach consisted of experiments in a VR-based test environment, combined with questionnaires and debriefing interviews. For the experiments, a multi-source data collection method was devised with a mix of automatic and semi-automatic data recording programmes. The experiments were set up with the aim of simulating real world wayfinding scenarios in an immersive VR-based test environment. The multi-source data collection method aimed to capture data on information transactions and overt behaviour in real-time. The conventional questionnaires conducted before and after wayfinding experiments were used to gain a range of information about each participant, their feedback and the knowledge that they felt they had gained. Taken together, the overall approach provides a range of data on individual spatial abilities, spatial information acquired, spatial locations, task performance and overt interaction behaviour. Such data could then be integrated and analysed for investigating spatial information transactions and the interaction between the three main elements: individuals, mobile devices and environment. These details of the methodology are now discussed in relation to Figure 5.2.

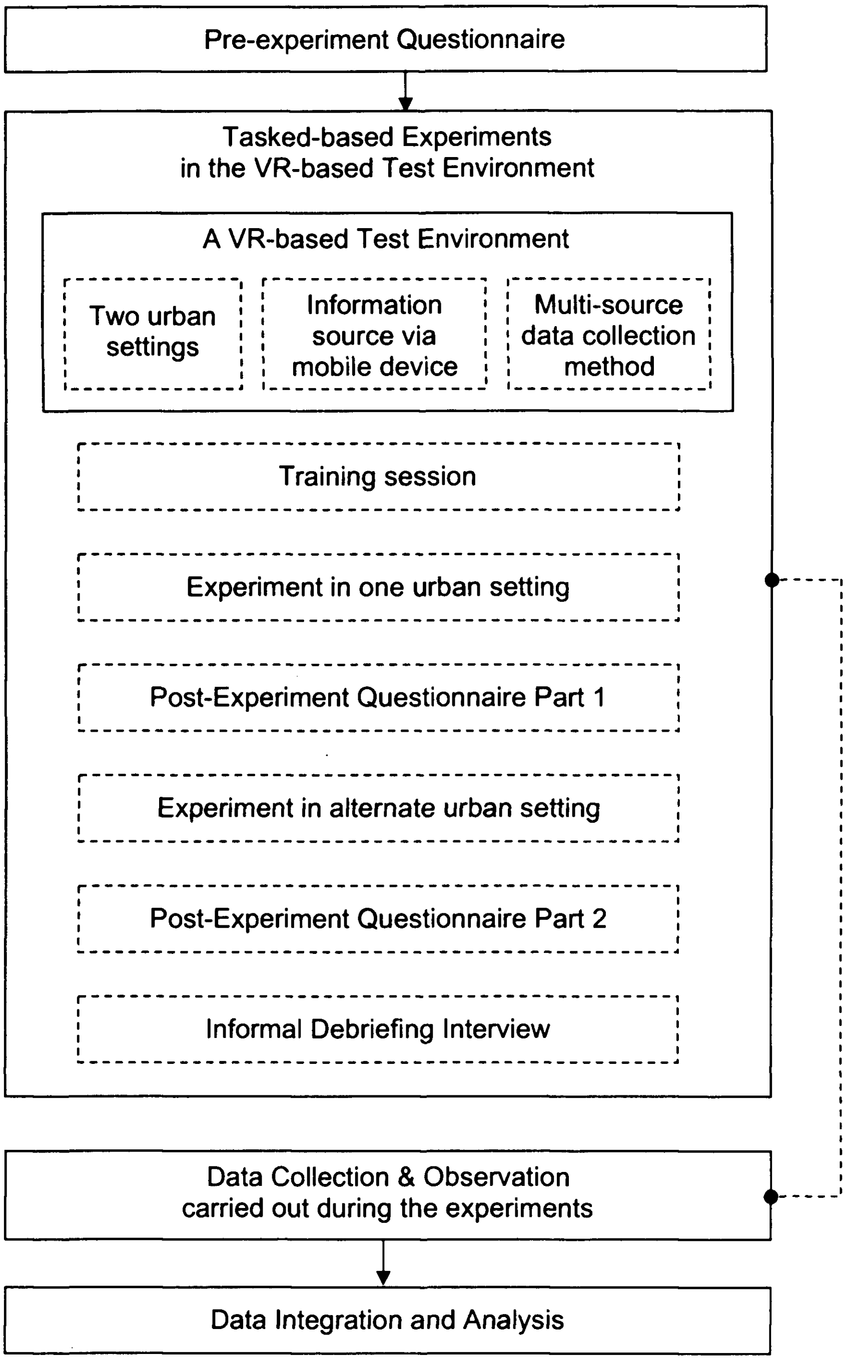


Figure 5.2 The elements of the methodology.

The main objective of setting up a pre-experiment questionnaire was to gain understanding of individual spatial ability, and their familiarity in using spatially enabling technologies. People's estimation of their sense of direction is believed to reflect their abilities to comprehend surrounding environments, to orientate themselves and to navigate: "A sense of direction is also derived from the perception of the known environment within which people move" (Gibson, 1979). Thus, self-reporting (also referred to as self-rating) questionnaires have been used to gauge participant general spatial ability and to provide indicators of ability to perform spatial tasks such as wayfinding. Such tools typically comprise a number of questions aimed at rating individual 'sense of direction' and rating their ability to perform various tasks. Kozlowski and Bryant (1977) consider that a sense of direction is an ability or trait that people can reliably identify as characteristics that they possess to a greater or lesser degree. A number of studies have demonstrated that people's self-reported measures of their sense of direction and spatial ability is a valid indication of their ability in wayfinding in large-scale environments (Montello, *et al.*, 1999; Hegarty *et al.*, 2002; Cornell *et al.* 2003). In this research, a questionnaire was proposed to be applied to reveal individual spatial ability, including questions relating to sense of direction, general spatial ability and spatial anxieties. The construction of this questionnaire drew on the previous research mentioned above, and the detailed design of the questionnaire is discussed in Chapter 6. In addition, an intention of this questionnaire was also to collect data on people's self-reported tendency for landmark-, route- or survey-centred thinking (Pazzaglia and de Beni, 2001). These were discussed in Chapter 3 as widely recognised types of spatial knowledge: landmark, route and configurational knowledge. The data collected from the questionnaire could, therefore, indicate the differences between individuals in terms of their self-assessed spatial abilities. The data could then be analysed with the real time data collected during the wayfinding experiments. Also included in the questionnaire were a number of questions on the individual usage of related technologies, such as mobile phones, PDA, the Internet and different forms of virtual realities. The purpose of setting up these questions was to identify variations amongst the selected participants in terms of familiarity with technologies. If different levels of the familiarity were to be reported amongst participants, their influence on the outcomes of the wayfinding experiments might then need to be considered.

An immersive VR-based test environment was proposed for carrying out the simulated real world wayfinding scenarios, aimed at offering a stable setting within which to study interactions and spatial information transactions at an individual level. The main focus of the test environment was to provide realistic yet controlled environmental settings in which individuals could access information through a mobile device in order to assist themselves in completing tasks, and where information transactions and user interaction could also be observed and recorded for analysis. This test environment comprised of Virtual Reality (VR) models of urban settings, a mobile device as information source and a multi-source data collection method for recording data on movement, information usage and actions. VR has several important characteristics useful as creating a test environment. First of all, when setting up a test environment in VR, it can be purpose built. For instance, different types of road network layout can be created and special landmark buildings can be located for evaluating how people find their way in response to these features. Another important feature of VR is that it can provide a controlled test scenario for experiments. Interference factors (deemed extraneous to the experiment) that might affect the experiment in the real world can be removed. In researching wayfinding, the experiments might need to be conducted over several months, and to involve a number of participants. A real urban environment may change during this time period, in terms of, for example, lighting conditions, weather conditions and effects of seasonality. The lack of control over extraneous factors may bias the resulting data and confound analysis. The VR-based test environment provides a consistent setting that is equally unfamiliar to each participant who is requested to undertake clearly defined tasks. Any interference which is not specified within the remit of the investigation can therefore be avoided. The behaviour of participants can then be analysed on a much more equivalent basis. In addition, a VR-based test environment allows experiments to be monitored more easily and intensively. Participant movements can be recorded by the VR tracking system. Participant actions and overt behaviour can be closely observed either directly by the investigator or through automated means – which would be much more challenging in a real environment.

Figure 5.3 illustrates a range of test environments in relation to key dimensions of realism of the environment, interaction with the environment and control of the experiments (Mallot *et al.*, 2002). The real world (RW), construed as an experimental environment, has the advantage of being 'real' and allowing participants a high degree of interaction with it. However, on the downside, there is a lack of direct manipulation or control of confounding factors in the experiments. For the classical psychophysics (PP) type of test environments (that is, methods of studying the relationship between body and mind, usually carried out in laboratory situations), experiments can be well controlled but with very low levels of realism and with only limited interaction with the environment. Computer graphics psychophysics (CG) can provide a high level of realism along with control of the experiments, but there is not much interaction with the environment. VR, in comparison with these other test environments, can produce high levels of realism and environmental interactivity, whilst retaining a sufficient level of control over experimental conditions. Although there are concerns regarding the similarity of the experiences, memory and knowledge acquired between the real world and virtual reality (discussed in Chapter 4), the emphasis of this VR-based test environment is upon the way in which individuals complete their wayfinding tasks and interact with mobile devices for accessing information.

The desired objective in the research reported here was for participants to replicate their usual wayfinding strategies in the VR test environment. In order to test the extent to which this was achieved, a debriefing questionnaire and interview was set up for obtaining participant feedback with regard to this issue (discussed further below).

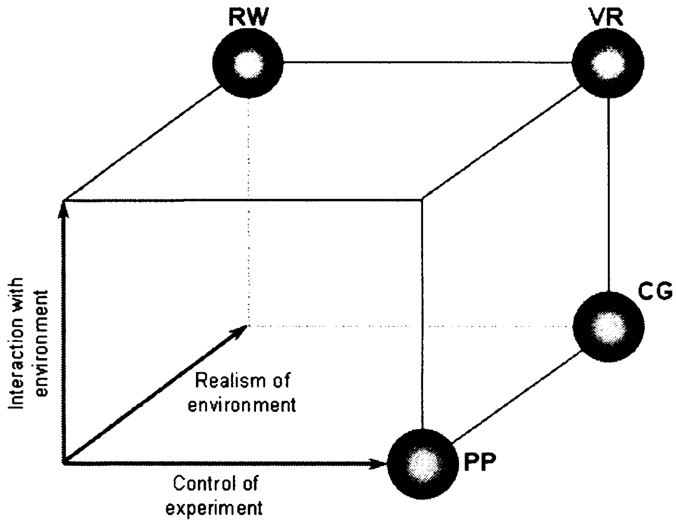


Figure 5.3 A range of experimental methods in relation to characteristics of interactivity, realism and control. (RW = real world experiments, VR = virtual reality, CG = computer graphics psychophysics, PP = classical psychophysics). Adapted from Mallot *et al.* (2002).

Within the test environment, and on the basis of knowledge of the literature, it was considered important to create contrasting urban settings. The reason for this derives from the fact that individual wayfinding strategies may be influenced by the urban morphology itself (Lynch, 1960; Gollege and Stimson, 1997). Consequently, and as further described in detail in Chapter 6, two contrasting urban models were constructed with their own distinctive layouts and mix of architectures. The layout of one of them is characterised by grid-like street patterns and modern low-rise housing. The other is characterised by a more irregular layout with the features of a traditional market town. Both are modelled on real UK towns.

The second component of the test environment is an information source delivered via a mobile device. This is an important new element in VR-based wayfinding experiments that allows participants to undertake more complex tasks since they have an interactive source of information upon which to call for assistance. A key theme of the mobile device is to simulate LBS wayfinding applications so as to research likely information usage from such services. The information that could be delivered via a mobile device could take a number of forms, including written text, the spoken word, graphical symbols, photographs, 2D maps, 3D maps, video clips, VR scenes, and audible tones. For the purposes of the experiments, the mobile device was a PDA with modes of communication restricted to text, voice and 2D maps (general layout map and zoomed-in detailed maps). This moves beyond the use of a single mode of communication for delivering information (most frequently the map) and allows wider testing of preferences.

The third component of the test environment is the multi-source data collection method. The objective of setting up this test environment is to study the interaction between the individual, the mobile device and the environment. One of the challenges has been to capture this process. Therefore, a multi-source data collection method has been established in the test environment which is able to capture and integrate spatio-temporal data of respondent position/location within the environment, data on information access via the mobile device and data on respondent behaviour. This aims to ensure that adequate data are collected with which to analyse the interactions and information transactions. The data thus collected would include: positional data; information usage (frequency, types of spatial information accessed and used) through the PDA; participant actions and reactions through observational data.

The experiments to be carried out in the VR-based test environment discussed above were in the form of having to complete sets of wayfinding tasks. In general, three broad categories of wayfinding tasks have been recognised (Allen, 1999). The commuting type of wayfinding concerns travelling between familiar places along familiar routes. The exploratory type mainly considers the activities of exploring a surrounding environment starting from a familiar place and returning to the place of origin. Goal based wayfinding relates to tasks when travelling to reach some novel destination(s). This last type of activity is often assisted by the provision of spatial information either via maps or instructions. The wayfinding experiments in this research were set up based on this last type of wayfinding activity, which will be referred to as 'task-based wayfinding' in this thesis.

The objective of the research is to study spatial information transactions and the nature of interactions between individuals, mobile devices and environments. In the set up of the task-based experiments, individuals were required to complete sets of wayfinding tasks in order to find pre-specified destinations in two different urban settings. During the wayfinding tasks, individuals could utilise a mobile device in order to retrieve spatial information that would assist them in completing their tasks. The mode of travel in the experiments was set as pedestrian. Compared with other modes of travelling, pedestrian wayfinding has fewer constraints on the way in which participants could access information. For example, one should not study maps in detail or read written instructions while driving, nor can one stop or necessarily reduce speed at any location whenever one desires in order to request and absorb information. There are also spatial constraints such as one-way systems and general conventions of the Highway Code.

For the settings where the experiments were to take place, urban areas were considered most appropriate. Urban areas provide a level of complexity that is yet tractable for wayfinding activities, whereas rural areas might have less changeable features and more open space in similarly sized spaces. Moreover, wayfinding in urban and rural areas are quite different in terms of orientation, view points, landmarks and distance. Consequently the types and levels of information required would also be different. The scope of this research is focused only on pedestrian wayfinding in urban areas. Moreover, the urban areas for carrying out the experiments were set up as un-familiar areas for all participants, aiming to eliminate the different levels of previous knowledge that might occur amongst the participants. Each participant would therefore commence the tasks on an equal footing. Before starting wayfinding experiments, a training session was introduced for all participants in a similar way to which experiments would be carried out, but in a different, much simpler urban setting. The purpose was to familiarise participants with the equipment, environment and procedure, and to reduce the learning curve effect during the main experiments. Two sets of wayfinding tasks were set up, with one set of tasks to be carried out in one urban setting and with another similar set of tasks to be carried out in another (see §6.4 for detail). The sequence of these two urban settings was alternated amongst the participants in order to counterbalance, and allow study of, any further learning effects that might occur. Another aspect of setting up the wayfinding tasks was the provision of information for assisting participants in completing the tasks. The spatial information transaction was aimed to be recorded through the actual wayfinding activities during the experiments. Therefore, an approach of 'choose information as you prefer' was adopted. That is, all participants could access the available information from the PDA as they needed at any time. This was aimed at reducing any bias that would undoubtedly arise where groups are pre-assigned a specific mode of information, regardless of any differences in individual information preferences amongst the participants.

The objective of setting up post-experiment questionnaires was to elicit feedback from participants after each set of wayfinding tasks, in order to reflect upon the following three aspects:

- Participant feedback on their experience of a VR environment regarding their 'sense of presence' (discussed in Chapter 4). More importantly, participant feedback on the commonality between their wayfinding strategies used in a virtual test environment and those used by them in the real world.

- The usefulness of the information provided through the PDA.
- Conventional route description and sketch map drawing to recall their journey.

The questionnaire was devised in two parts. Post-experiment question part I was to be carried out after the completion of the first set of wayfinding tasks, while part 2 was implemented after the completion of the second set of wayfinding tasks. The emphasis of questionnaire part I was upon participant experience in the VR test environment, such as their sense of 'being there', and the commonalties between wayfinding approaches adopted in the VR environment and those used in the real world. Drawing of a sketch map of the area with routes and any remembered features was also required. Route description and sketch map drawing tasks were ways to measure individual spatial knowledge gained (as discussed above) as a static situation.

In order to establish whether there was consistency in the feedback in the similarity of wayfinding strategies used in VR and in the real world, these same two questions were repeated in post-experiment part 2. The emphasis of the questions in part 2 was on the use of the information provided through the PDA, acting as the mobile device. The same route description and sketch map drawing tasks were also included here.

The purpose of setting up an informal de-briefing interview, after the experiments, was to confirm that all questions had been answered and fully understood as well as to provide an opportunity for participants to raise any particular issues they wished to address. Moreover, general participant feedback was solicited on their wayfinding experiences in the VR test environment in this informal de-briefing interview, particularly with regard to any differences in the wayfinding strategies that respondents used in their daily life when compared to those adopted in the VR test environment. All interviews were loosely structured around these purposes.

The objective of setting up a multi-source data collection method was discussed earlier in this Section and is a key component of the methodology. This method was devised to enable collection of data in real time, at a detailed level of spatial granularity, and for multiple variables including location, time, information access, information usage and overt actions. Data were collected for each individual while he/she was performing the wayfinding tasks. Data on location and information usage were collected through automated methods through a series of existing and specifically programmed software. Observation methods were also applied during the experiments.

All of the elements of the methodology described here were developed and honed through a cycle of design, prototyping, testing, design improvement and utilisation for the final experiments. The testing of the prototyped elements is described in Chapter 6.

The data collected from the questionnaires and the experiments were intended to be integrated and analysed at different levels (individual and aggregate) and from different aspects. Both quantitative and qualitative analyses were deemed necessary in order to leverage maximum insight from the research.

CHAPTER SIX
Design and Setup of the Experiments

Following the methodology established in Chapter 5, this Chapter focuses on the design and set up of the experiment and all its elements. The Chapter is structured into five sections. The first Section describes how the pre-experiment questionnaire was complied. In §6.2, the creation of a test environment, which consists of implemented VR urban models, simulated wayfinding assistance delivered via a PDA and a multi-source data collection method, is described. §6.3 describes the set up of the two parts of the post-experiment questionnaire. §6.4 provides a description of the design of the task-based wayfinding experiment procedure. Finally, §6.5 describes the implementation of a prototype prior to conduct of the main experiment.

6.1 Creating a pre-experiment questionnaire

As discussed in the previous Chapter, the main objective of this pre-experiment questionnaire is to obtain background information about participants, including their demographics, self-assessed spatial abilities and their familiarity with a range of technologies. The intention is to analyse these data alongside the behavioural data recorded during the experiments. Although some of the data collected may not be used as variables in later analyses, such as age, ethnicity and occupation, the data provide some level of understanding of the individual participants and the generalisability of the research findings. Another reason for the timing of this questionnaire before the experiment is so that individuals' assessments of their spatial abilities will not be influenced by their experience of the wayfinding experiments.

The pre-experiment questionnaire was designed to be self-administered, which means that participants would be required to record responses to all questions without investigator supervision. All questions were structured with tick boxes indicating the degree of accord with the given statements, and all questions were closed. The content of this pre-experiment questionnaire was structured into four main parts:

- demographic information;
- self assessment of spatial ability;
- familiarity with related technologies;
- spatial-visual test.

Following the first part of the questionnaire requesting an individual's gender, age, ethnicity, qualification and occupation, the main part of the questionnaire aimed to measure individual spatial ability through a range of attitude-focused questions. In this part, the questions were devised with reference to other pre-existing questionnaires discussed in the literature (e.g. Montello *et al.*, 1999, Pazzaglia and De Beni, 2001; Hegarty *et al.*, 2002). The aspects of individual spatial ability are discussed in §3.2.2. The questionnaire was initially structured to reflect different aspects of people's spatial abilities and awareness using 21 questions. Table 6.1 lists the 21 questions (Q1 to Q21), grouped into nine aspects marked as A1 to A9. These nine aspects include sense of direction, preference for image thinking or verbal thinking, tendency towards landmark/route/map (configurational) thinking, as well as map usage, general ability in performing spatial tasks and spatial awareness. Aspects A4 through A6 are not intended to be mutually exclusive but aim to establish any tendency in the preference for the three generally recognised types of spatial knowledge (landmark, route, configurational) as discussed in Chapter 3. The draft questionnaire was then tested on 89 participants. The process of evaluating the questionnaire will be discussed in detail in §6.5.1. After analysing the results of the questionnaire and considering the feedback from the participants, a number of modifications were made. Reasons for these modifications can also be found in §6.5. The revised version of the questionnaire, shown in Table 6.2, has seven aspects with the seventeen questions. Tick box answers to the questions were designed on a six point scale based on the level of agreement with the question posed from 'strongly agree' to 'strongly disagree'.

A1	sense of direction	**Q1** My "sense of direction" is very good. **Q2** My family/friends think that I have a good sense of direction. **Q3** When I'm in a complex building (many floors, stairs, corridors), I can indicate where the entrance is immediately. **Q4** When I'm in a natural, open environment (e.g. countryside), I naturally know where north, south, east, and west are. **Q5** When I'm in my hometown, I naturally know where north, south, east, and west are.
A2	preference of image thinking	**Q6** When someone is describing to me the route to reach an unfamiliar place, I prefer to make an image of the route.
A3	preference of verbal thinking	**Q7** When someone is describing to me the route to reach an unfamiliar place, I prefer to remember the verbal description.
A4	tendency towards route thinking	**Q8** I usually orientate myself by remembering routes connecting one place to another
A5	tendency towards landmark thinking	**Q9** I usually orientate myself by looking for features (landmarks) that are well-known to me.
A6	tendency towards map (configuration) thinking	**Q10** I usually orientate myself by trying to create map-like image of the area.
A7	Map use	**Q11** I like using maps. **Q12** I am very good at reading maps. **Q13** After reading a map once, I need to keep referring to it in order to find my way.

A8	general spatial ability, such as judging distance, wayfinding	**Q14** I am very good at judging distances. **Q15** I do not get lost very easily when visiting unfamiliar places. **Q16** I don't confuse right and left turns. **Q17** I remember routes very well while riding as a passenger. **Q18** If I go to a new place, I easily know the way back.
A9	spatial awareness and spatial anxiety	**Q19** I'm confident in finding my way when going to new places. **Q20** It is important to me to know where I am. **Q21** I like to explore unfamiliar places.

Table 6.1 The initial version: nine aspects relating to individual's spatial ability (questions subsequently dropped/modified are printed in grey).

A1	sense of direction	**Q1** My "sense of direction" is very good. **Q2** My family/friends think that I have a good sense of direction. **Q3** When I'm in a complex building (many floors, stairs, corridors), I can indicate where the entrance is immediately. **Q4** I tend to think of my environment in terms of cardinal directions (North, South, East, West). **Q5** I am very good at giving directions.
A2	tendency towards route thinking	**Q6** I find my way best by remembering the routes connecting one place to another.
A3	tendency towards landmark thinking	**Q7** I find my way best by looking for recognisable features (landmarks, e.g. pub, petrol station).
A4	tendency towards map (survey) thinking	**Q8** I usually orientate myself by trying to create a map-like image of the area.
A5	Map use	**Q9** I like using maps. **Q10** I am very good at reading maps.
A6	general spatial ability, such as judging distance, wayfinding	**Q11** I am very good at judging distances. **Q12** I do not get lost very easily when visiting unfamiliar places. **Q13** I remember routes very well while riding as a passenger. **Q14** If I go to a new place, I easily know the way back.
A7	spatial awareness and spatial anxiety	**Q15** I'm confident in finding my way when going to new places. **Q16** It is important to me to know where I am. **Q17** I like to explore unfamiliar places.

Table 6.2 The revised questionnaire: seven aspects of people's spatial ability.

The third part of the questionnaire consists of a number of fact-focused questions on the individual's usage of related technologies. Through these questions it should be possible to detect variations amongst the selected participants in terms of familiarity with technologies. If familiarity were at different levels then its influence on the wayfinding experiments may need to be considered. The first four questions were designed to elicit frequency of usage of mobile phones, palm computers, text messaging and electronic games. The frequency rate was set from daily use, 2-3 times a week, occasionally use, rarely use and never use. The next question was about using maps and/or travel instructions through the Internet. Considering the general usage differences of mobile devices and map/travel information sites, the question was set up using a different scale as weekly, monthly, 2-5 times year, rarely and never. An additional question was about the experience of various types of virtual reality. The responses from these questions would give a good indication on the level of familiarity with these technologies among the selected participants. The full pre-experiment questionnaire can be viewed in Appendix II.

The last part of the pre-experiment questionnaire (see Appendix II) entailed a visuo-spatial test. The test was created for this research based on a visuo-spatial ability test used by the Department of Radiography at City University for testing aptitude in students. The test consists of five questions (Appendix II) with an intention of gradually increasing complexity. All five questions involve mental manipulation and visualisation of images and objects (see §3.4on psychometric measurement in Chapter 3). It is recognised, however, that this type of test may be a weak indicator of wayfinding ability (Sholl, 1998; Tackeuchi, 1992), but was included nevertheless in order to gain better understanding of individual ability.

6.2 Building a test environment

A test environment was set up for carrying out experiments to study the interactions and information transactions between environments, individuals and mobile devices. This Section describes in detail how such a test environment was created. The test environment was designed around three main components:

- Virtual Reality (VR) urban models and a projection system, which allowed individuals to 'walk around' at street level with realistic views;
- a mobile device (a PDA), used to provide a simulated LBS , providing route and map wayfinding assistance to people on the move;
- software for multi-source data collection, to record participant actions, interactions and reactions during experiments within the test environment.

6.2.1 Test environment part 1 – VR urban models

There is an important distinction between VR models, which offer the ability to walk through realistic street scenes, and other models which are created for birds-eye views and 'fly throughs' of urban areas but which do not contain the necessary realism at street level. These two approaches serve different objectives (Batty & Smith, 2002). The objective of the VR models in this test environment is to create sufficient realism at street level such that participants, as pedestrians, might reasonably be expected to behave (in wayfinding terms) as they would in a real street scene (discussion on this is provided in §6.2.3 with respect to a post-experiment questionnaire and in Chapter 8 with respect to analysis of the experiment results). This has implications for the level of detail that needs to be achieved and the corresponding consistency of that detail (Tromp et al., 1998). The focus here is on the construction of urban VR models since the studied wayfinding activities are in urban areas. A four stage process has been adopted in creating the urban VR models, as illustrated in Figure 6.1.

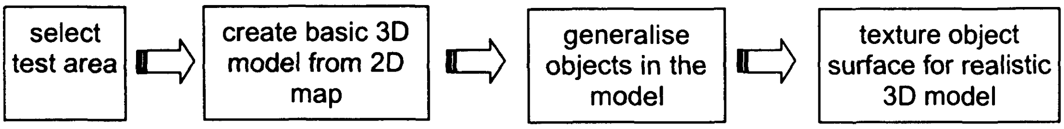


Figure 6.1 Four stage process of VR model creation.

Test areas need to be carefully selected so that they are suitable for achieving the specific experimental objectives, that is, they contain the types of features pertinent to testing a particular set of wayfinding activities. Moreover, the layout of the specific built environment is likely to affect how participants will respond to them in different situations (Lynch, 1960; Gollege & Stimson, 1997). In order to reflect this, more than one model has been used. Thus, two contrasting urban models have been constructed, each having its own distinctive layout and mix of architectures. The layout of one of them is characterised by grid-like street patterns and modern low-rise housing, covering an area of approximately 48 hectares (approx. 800m by 600m). The other is characterised by a more irregular layout with the features of a traditional market town, covering an area of approximately 35 hectares (approx. 700m by 500m). The layouts of these two selected areas are shown in Figure 6.2 (a) and (b) respectively. These two urban models will be referred to as urban setting U1 and urban setting U2 throughout the thesis. Both are modelled on parts of real UK towns: a residential area of Milton Keynes and the town centre of Saffron Walden. Although both are mentioned in the Doomsday Book (1086), Milton Keynes was planned and developed as a new town starting in the 1960s, whilst Saffron Walden has retained its basic old street layout and many old building styles. Almost all of the features in these two models were based on the reality of both areas. The only exceptions to this rule for setting U1 were the changes of the destination landmarks to make them more easily recognised for the purpose of wayfinding experiments. These were: a modern church façade and its spire used to replace a Christian Centre that, in reality, had a very similar façade to the surrounding buildings; a typical corner shop type of post office and a McDonalds fast food restaurant were added at two destination locations; and a cinema façade was added instead of the original building façade at another destination. For the same reason, in setting U2, the features which are different from the reality are the names of shops and pubs (not the buildings themselves) such as the name of the superstore and the name of the 'George and Dragon' pub.

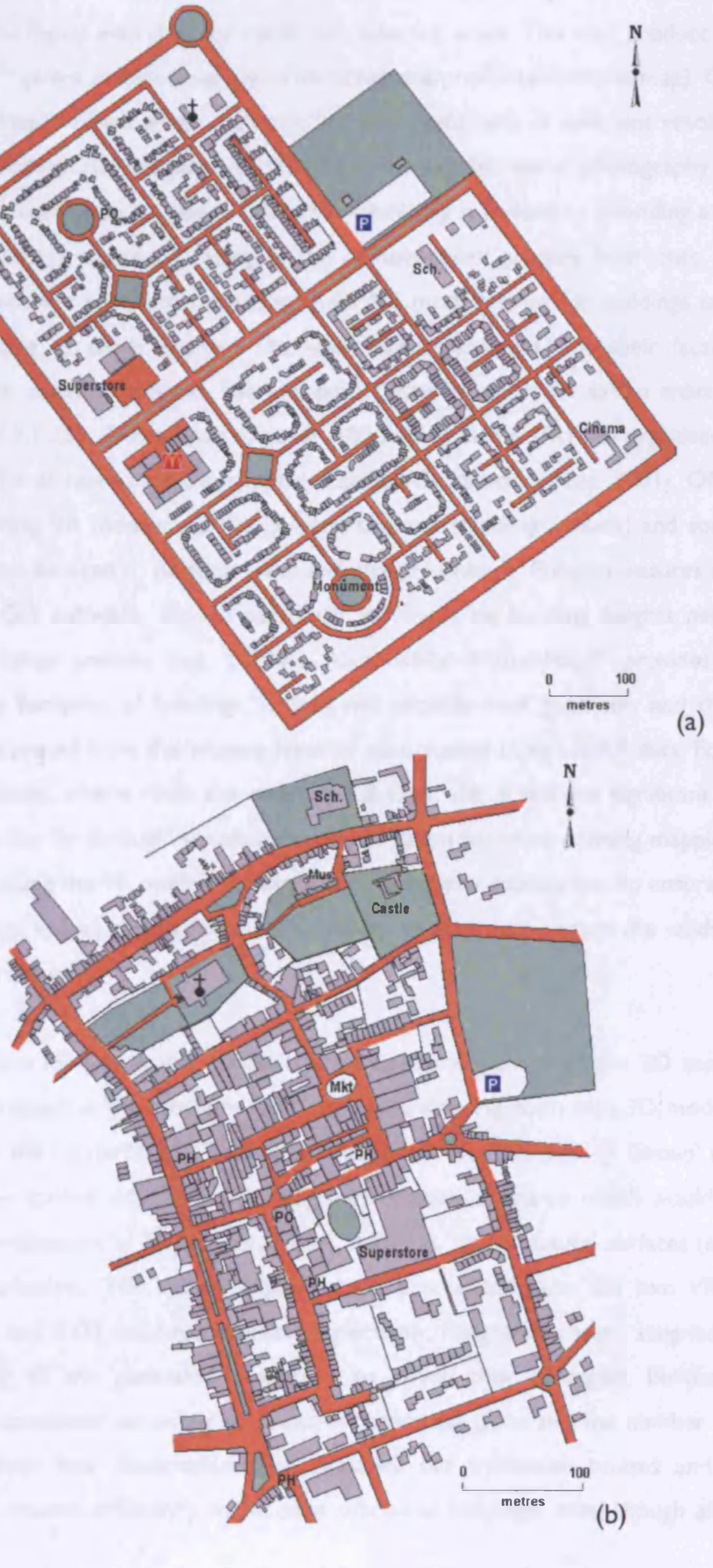


Figure 6.2 Plan view of the two selected urban areas: (a) setting U1; (b) setting U2.

Having selected test areas, the next stage was to create basic three-dimensional (3D) models from two-dimensional (2D) digital maps. Initial 3D models were generated by extruding objects presented in 2D maps. Great Britain's national mapping agency, Ordnance Survey, agreed to provide digital map data for these two selected areas. The map product provided was MasterMap™ (www.ordnancesurvey.co.uk/oswebsite/products/osmastermap). Ordnance Survey's MasterMap™ offers image, polygon, line and point data at sufficient resolution for building urban models. The imagery layer is fully orthorectified aerial photography in 24 bit colour at a 25cm resolution. Its use in urban VR modelling is limited to providing a textured ground surface, where desired. Draping of the orthorectified imagery layer onto extruded objects cannot provide adequate realism in these VR models since for buildings only roofs (not usually visible in street scenes) are well represented but not their façades. The topographic layer contains polygon, line and point features which for urban areas are at a notional scale of 1:1,250. These features (over 400 million in the UK) are organised into 21 descriptive groups of real-world topographic objects (Ordnance Survey, 2001). Of greatest interest for building VR models are the polygon features (buildings, roads) and some point features which can be used to position trees and street furniture. Polygon features are easily extruded using GIS software, though additional attributes on building heights need to be obtained from other sources (e.g. LiDAR). Also, whilst MasterMap™ provides detailed geometry of the footprint of buildings, it does not provide roof geometry and this either needs to be interpreted from the imagery layer or constructed using LiDAR data. For street-level VR applications, where roofs are rarely in full view, this is not the significant problem that it would be for 'fly through' visualisations. The reason for using existing mapping as the basis for constructing the VR models rather than devising new models was to ensure that the urban morphology was as close as possible to reality so as to help ensure the validity of the wayfinding experience.

For the two urban models in this research, the real-world objects in the 2D topographic layer were generalised at the attribute level prior to extruding them into 3D models. Thus by inspection of the MasterMap™ 'Legend' attribute and the 'Description Group' attribute, objects were re-classified into five main categories: special landmarks which would need to be specifically constructed in 3D (e.g. churches), buildings, roads, natural surfaces (e.g. green space) and walls/hedges. The initially clipped areas that would form the two VR models comprised 3954 and 2235 individual objects respectively. Height data were assigned to each object according to the generalised category to which they belonged. Building height attributes were calculated according to broad architectural types and the number of floors was obtained from field observation. For example, old traditional houses and historic landmarks were treated differently to modern office-like buildings, even though all may be described as 'low rise'. Natural surfaces and roads were given notional heights of 0.1m. 3D models were then extruded from the 2D map data using ArcGIS™ and exported as Virtual Reality Modelling Language (VRML) format. However, the objects in the urban models extruded in this way have many surfaces because of the complex shape of buildings and the way by which ArcGIS™ extrudes objects as triangular facets. Taking a building object as example, Figure 6.3(a) shows the footprint of a single building object in 2D map format (from OS MasterMap™), whilst Figure 6.3(b) shows the plan view of the extruded 3D object of the same building. Figure 6.3(c) is a façade (profile) view showing how the triangular facets make up the façade (coloured to assist visualisation). Although the basic extrusion technique provides generally realistic structures upon the digital foundations of building footprints, difficulties nevertheless arise in texturing buildings using digital photographs of the facades. Furthermore, complex feature geometry creates very large executable files which become difficult to run as smoothly flowing VR models. For this reason, our models required further generalisation, pruning and simplification.

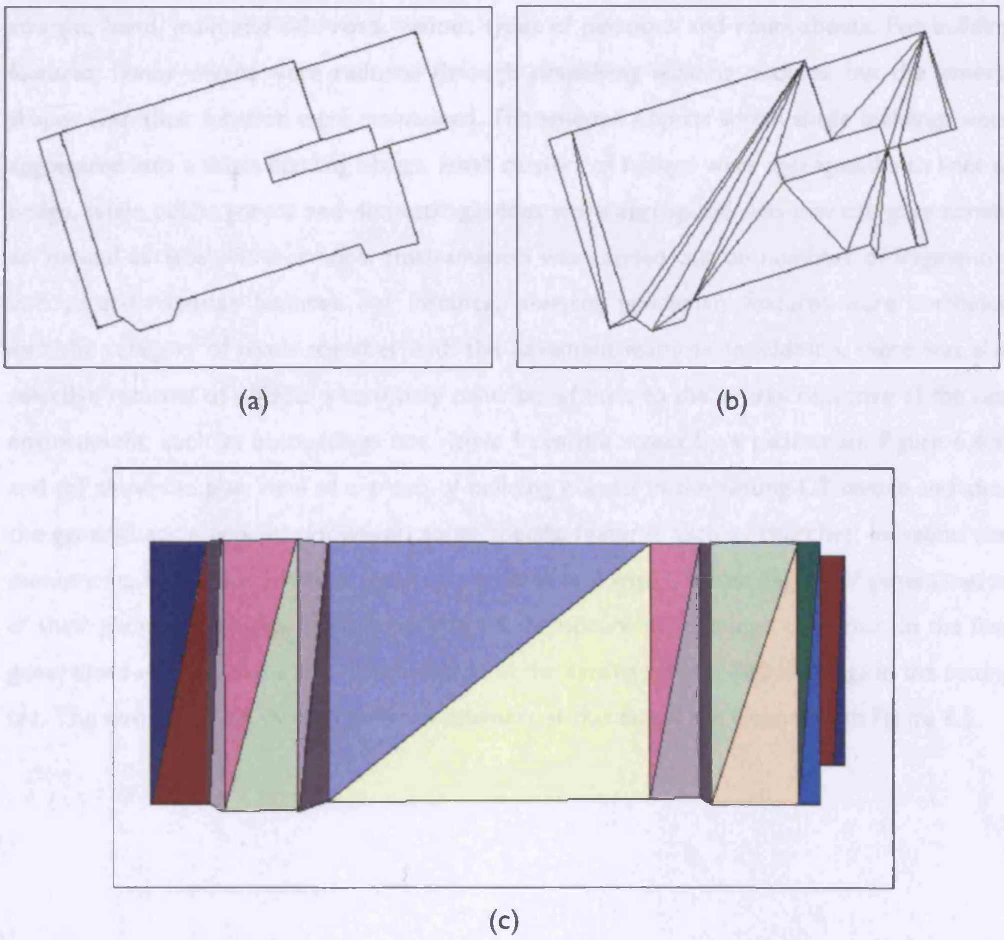
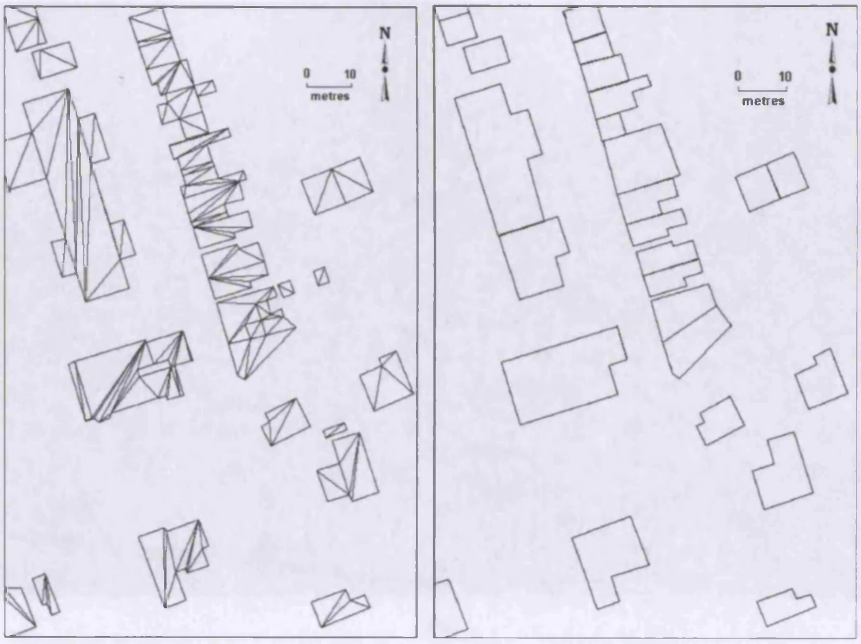


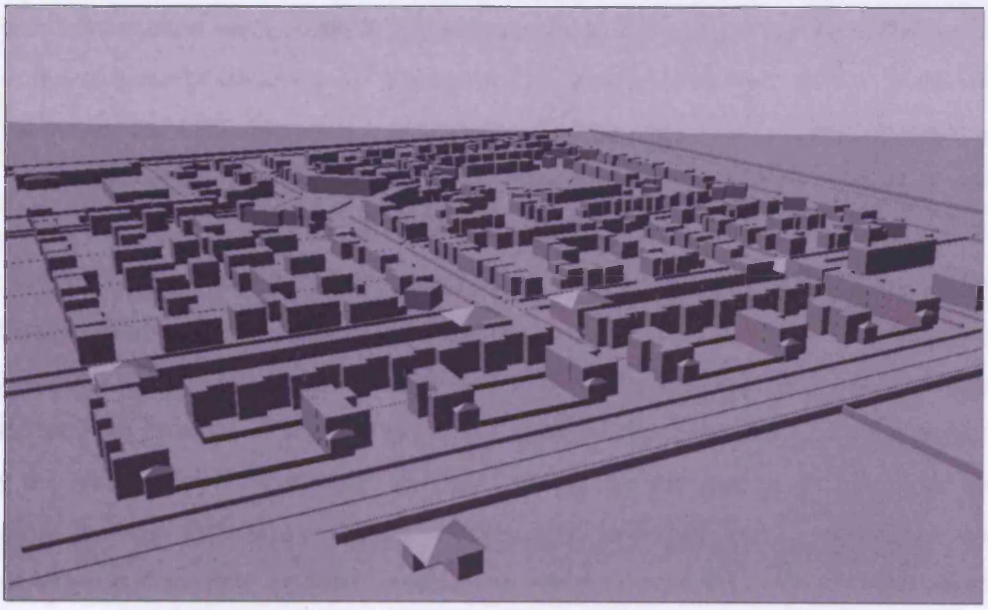
Figure 6.3 A single building object: (a) the footprint of the object from OS MasterMap; (b) the plan view of the extruded object; (c) façade view of the object.

The next stage of creating the VR models was to generalise objects in the models. In setting up test environments, it is both unnecessary and difficult to provide exact replicas of real urban areas. The models were created with the aim of having consistent degrees of abstraction and detail whilst retaining sufficient realism for the application at hand. In this research, the smooth running of a VR model with natural perspective views was assigned higher priority than incorporating precise details of the geometric shape of buildings and roads. Thus a generalisation process was applied to the geometric shapes of objects in the two models. The generalisation process adopted here has been based on similar principles to those of map generalisation (McMaster & Shea, 1992; Muller et al., 1995). First of all, simplification was applied particularly to shapes of buildings and road objects, with aggregation also on buildings and hedge objects. These processes were carried out manually, mainly through a consideration of a desired set of criteria on shape, location and the character of entire objects. This was thus based on the principles of generalisation rather than on specific vector and/or raster generalisation algorithms. Taking the example of road features, road lines were considerably simplified through reducing the number of points along the feature lines on the basis of still retaining the general character of roads such as straight, bend, main and side road, various types of junctions and roundabouts. For building features, minor details were reduced through simplifying building outlines, but the general shapes with their location were maintained. Triangulated objects within single buildings were aggregated into a single building object. Small clusters of hedges were aggregated into lines of hedge, while public greens and domestic gardens were aggregated into one category named as 'natural surface'. Furthermore, amalgamation was carried out on numbers of fragmented in-road and roadside features. For instance, 'sleeping policeman' features were combined into the category of roads together with the pavement features. In addition, there was also selective removal of objects where they contributed little to the overall objective of the test environment, such as outbuildings not visible from the street by a pedestrian. Figure 6.4(a) and (b) show the plan view of a group of building objects in the setting U2 before and after the generalisation process. However, some specific features such as churches, museums and monuments have been left with much more detail and with a lesser degree of generalisation of their geometric shapes in order to more fully capture their unique character. In the final generalised models, there are 1250 buildings in the setting U1 and 780 buildings in the setting U2. The two urban VR models (without textures at this stage) are illustrated in Figure 6.5.

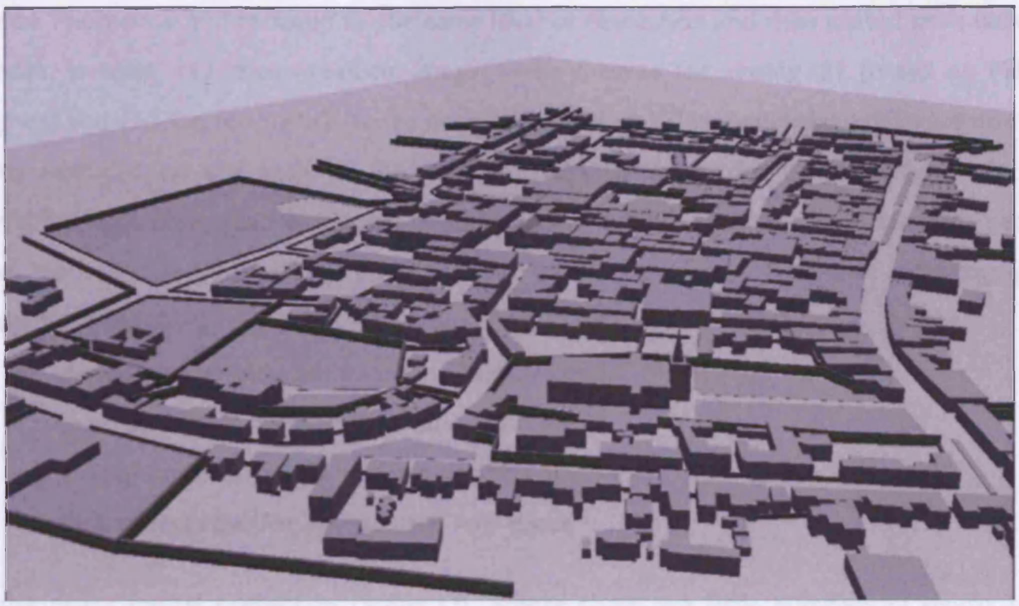


(a) (b)

Figure 6.4 The plan view of a group of building objects in setting U2: (a) before the generalisation process; (b) after the generalisation process.



(a)



(b)

Figure 6.5 Two basic urban VR models: (a) urban setting U1 viewed from the east; (b) urban setting U2 viewed from the north (for maps see Figures 6.2(a) and (b) respectively).

The last stage of creating the VR models was to texture object surfaces for photo- realistic 3D models. The main factors that were considered for texturing the facets of 3D objects in the test environment were: realistic appearance, vistas and consistency in the level of detail. Here, the purpose of texturing 3D objects was to create street-level realism in the VR test environments, from the perspective of someone walking along a street. The approach was to use street-level digital photographs taken during field work to capture a range of textures that exist. However, issues of overall file size restrict the number of photographic images that can sensibly be used and their resolution (dots per inch). For large, bulky models, an important parameter for the projection of VR scenes is the distance threshold for object inclusion in a scene. Thus, if set for example at a 100m threshold, models will run faster and smoother than if set at 500m, but any vistas will be limited to 100m. On the other hand, using the whole area without restricted vistas would give participants a much more realistic feeling of the walk through. Therefore, there is a trade-off between this parameter and the length of vistas that must be accommodated in order to maintain realism. This trade-off can be offset by reducing the numbers of individual photographic textures used and by lowering image resolution. For the models in this research, in order to maintain larger vistas, the resolution of photographic images was systematically degraded to a degree that was considered not to compromise building realism. In this way, sufficient variety of textures could be achieved in a smooth running VR model. All digital photographs were taken from real sites at Milton Keynes and Saffron Walden during field work. They were then rectified in

Adobe Photoshop and reduced to the same level of resolution and then pasted onto building façades. In total, 111 photo-realistic images were created for setting U1 (based on Milton Keynes) and 162 for setting U2 (based on Saffron Walden). The buildings in different districts were textured on the basis of the characteristics of those districts (see Appendix III). Inevitably, each photographic image has been used a number of times. Thus, the term 'repeat rate' has been used, for this purpose, to refer to the number of times that a photographic image has been used. It was defined as:

- repeat rate as zero: for images used only once
- low repeat rate: for images used >1 and <=5
- medium repeat rate: for images used >5 and <=10
- high repeat rate: for images used >10 times

In the urban model presenting setting U1, where there are large numbers of similar style houses in this residential area, each photographic image was used on average sixteen times. For special landmark buildings, images were used with repeat rate as zero, such as the church, the monument, the cinema and McDonald's. Some areas were identified as suitable for using images at medium repeat rate, whilst others were deemed suitable for high repeat rate. For the model representing setting U2 which is the central area of a traditional market town, each photographic image was used on average seven times. Similar to the setting U1, special landmarks were textured at zero repeat rate. The areas with shops were identified for using images at low repeat rate. Medium repeat rate was used for the areas with similar style of houses along the streets. In both models, these repeat rates were decided in the light of field inspection and were consistent with the variety of buildings encountered in the real environments. Roads, walls and hedges were also textured using photo-realistic images. Sample scenes from both VR models are given in Figure 6.6 and Appendix III.

(a)

(b)

Figure 6.6 Sample scenes from both urban VR models: (a) a view from model U1; (b) a view from model U2.

Another important and unique feature in urban environments, which cannot be extruded from 2D maps automatically, is street names and other signage. In our VR urban models, street name signs were added as additional object features. Two different forms of these 3D objects were created for the different urban settings according to their appearances in real environments. One was treated as a plaque object seen fixed on walls, and the other was as a street sign object mounted at the side of streets (see Figure 6.7).

Figure 6.7 Examples of street signs used in the VR models.

An additional small VR model was created for the purpose of carrying out a training session for participants to familiarise themselves with the technologies and being in an immersive VR. It was built in a similar way as described above. However, the model was not based on any real areas, with a simple spatial layout containing five streets. The main characteristic of the area was a mix of residential houses and a store and a couple of restaurants. It also contains two types of street signs used for urban settings U1 and U2.

A number of elements have not been built into the VR models, such as topography of the areas, street furniture, moving traffic and people. For the topography of setting U1, the real world area of setting U1 is quite flat terrain, therefore the area in VR model setting U1 with flat terrain quite reflects the area. For the real world area of setting U2 there is slight valley running through the centre of the town with a slight incline to the north where the church is located. This was not reflected in the VR model. The view of the church was not affected as the church spiral could still been seen from a distance. Moving cars and people have not included in the current VR models. Different elements in the VR models should be presented with a consistent level of detail (Vinayagamoorthy, 2004). Creating moving traffic and people and building them into the models at a similar level detail to the rest of the urban model created a challenge that would have needed more extensive research, and therefore can be considered in future research. A range of street furniture will also be considered in future studies.

6.2.2 Testing environment part 2 – information source

The mobile device is an important component of the test environment, since it acts as an information source that can be accessed interactively as a simulated LBS application. The information delivered via a mobile device could take a number of forms, including written text, the spoken word, graphical symbols, photographs, 2D maps, 3D maps, video clips, VR scenes, audible tones and so on. At present, the mobile device is taken to be either a PDA or a mobile phone, and in this research a PDA was used with modes of communication available as text, voice and 2D maps.

The structuring of information on a PDA needs to address the issues of mode of communication and level of detail provided. The approach adopted here was to use parallel strands for each mode of communication (e.g. text, voice, maps), structured hierarchically with increasing levels of detail, and to permit switching between modes. Thus in this test environment, provision was made for simulating LBS wayfinding instructions as text, voice and maps which were selectable according to each individual's personal preference. Information for any defined geographical area was then organised into three levels of detail. In each mode of communication, individuals could access information initially in a general form and then drill down to more specific information content. Thus in order to offer pedestrian wayfinding assistance, text instructions started with a list of routes identified by their start location and destination and followed by general route information on each route with further detailed instructions available for each section of route. Instructions in voice mode were designed in the same structure as the text instructions. For information presented as maps, the top level was a generalised sketch map featuring street layout. At the next more detailed level, various landmarks and road names could be overlaid onto the sketch map. A final option was to zoom the map to show the most detailed level of information. Figure 6.8 shows the general structure of the information on the PDA.

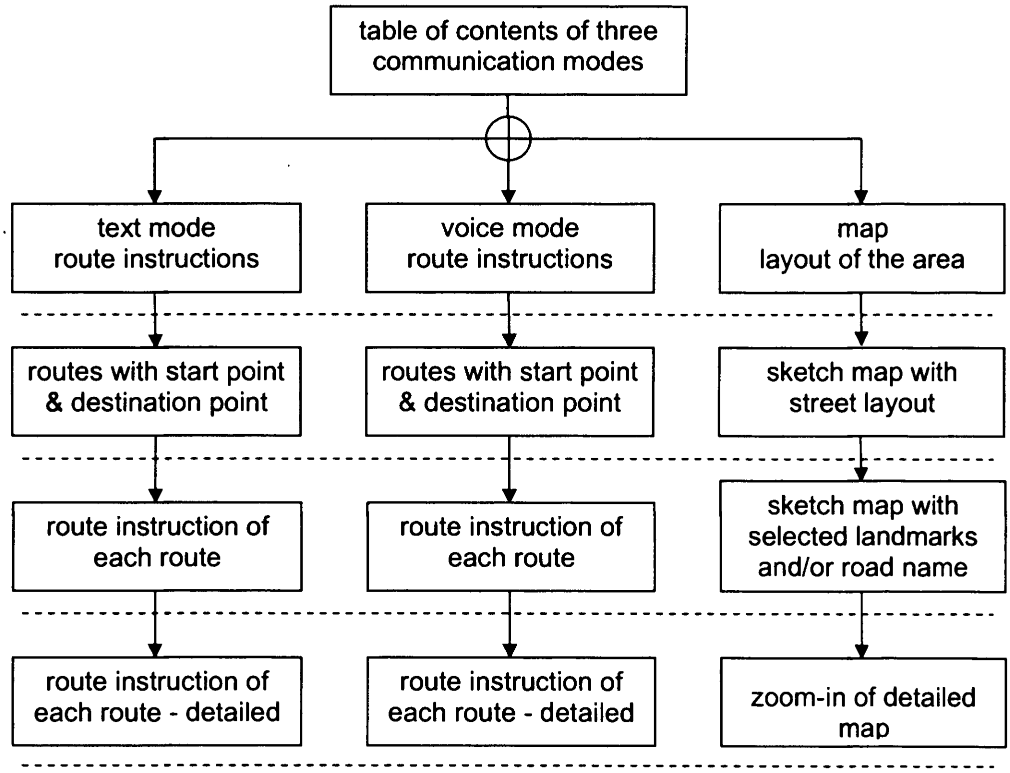


Figure 6.8 The structure of the information content on the PDA.

Having designed the structure of information on the PDA, the detailed content of the information was organised into two groups: route instructions from starting point to destination point for text and voice mode; and maps of the defined areas. Route instructions provide the sequential type of information using various features along and/or visual from the selected route and physical activities (e.g. turn, walk along) (Denis, 1999; Lovelace *et al.*, 1999). There is no consensus in the literature (Lovelace *et al.*, 1999) as to which components should be included in 'good route directions'. Suggestions have been made on the elements of route instructions. Such elements include upcoming points of choice, instructions for proceeding at choice points, use of landmarks (at choice points or along routes), use of directions, use of distances, use of linear sequential information and use of other instructive information (Wunderlich and Reinelt, 1982; Allen, 1997; Denis *et al.*, 1999). For the route instructions that were designed for the test environment, there were three main elements: direction/action from the starting point, actions/directions along the route and action toward destination point. Also the actions (e.g. turn left) were composed of the consistent components which were landmarks, orientations and actions, for example, 'at a location (e.g. the Cross-Keys Pub, or the T-junction at the end of some street) turn left'. The landmarks mentioned were either along the route or visible from the route, which could either be buildings (such as shops, pubs) or be road signs and road structures (square, roundabout, junctions). Another group of content information was presented as maps. The maps were used to show the layout of the surrounding area of wayfinding paths and destinations. As in most popularly used web sites for finding destinations (e.g. www.streetmaps.co.uk, www.multimap.co.uk, www.maps.google.com and www.mapquest.com), maps can be viewed at different scales with different levels of detail. In this test environment, maps were organised into two levels: one level of sketch map showing road layout with display of interactively selected landmarks and road names, and another level of zoom-in map with more detailed information in one part of the area at a time. In addition, there was also the information pertaining to the exact current position of individuals, which could theoretically be displayed on the PDA. However in this research, this information was not included. The reasons for this are twofold. Firstly, although the locations of individuals can be identified in the real world through location-aware PDA, this would be to different levels of accuracy depending on the positioning technologies used (GPS, cellular network based) and the nature of urban area (high-rise city centre, low-rise suburban). Hence, given current technologies, the location of PDA cannot accurately and consistently be expressed as a point in urban areas. Secondly and importantly, by not providing exact current position all participants are put on an equal footing regardless whether maps, voice or text are being used.

Following the defined structure and content of information, it was necessary to design a user interface for accessing information on the PDA. There were two broad options: it could either be a proprietary interface on the Windows CE platform, or developed using markup languages (e.g. HTML) and Java for an interface using an Internet browser. Both methods were explored in this research. Use of Visual Basic on a Windows CE platform offers flexibility of programming and style of presentation. On the other hand, use of a Web browser style interface provides for easy adoption on any device. Its style is also more intuitive, corresponding with people's experience of the Internet and thereby reducing the gradient of the learning curve in using any application. In addition, it provides an easy environment for modifying and testing the information content of pages. For this reason the

Web browser approach was adopted here for the display and access of information on the PDA. According to the structuring of content as discussed in the previous paragraph, Figure 6.9 illustrates a part of the Web page structure employed for the setting U2 and the hypertext links between them. On the PDA, navigation between pages is by means of touch screen using the handheld stylus.

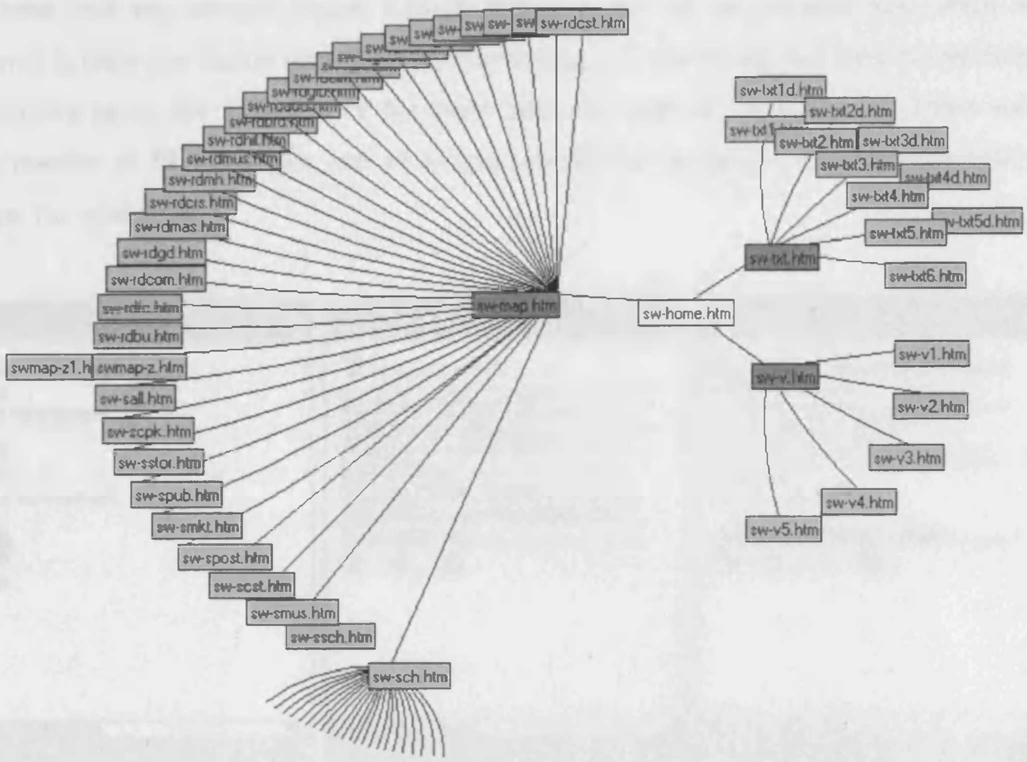


Figure 6.9 The structure of web pages with its hyperlinks as installed in the in PDA (upper levels of hierarchy only).

Currently, some basic guidelines should be considered when designing Web page content and style for mobile devices (Chu, 2002). The screen size of mobile devices is small – approximately 100x120 pixels for most mobile phones (some of the latest models have slightly larger screen sizes) and 240x360 pixels for palm PDA. Thus there are quite severe constraints upon display of content using small screens. Therefore, the focus for displaying information on the PDA is upon presenting essential information content with an adequate level of readability and providing easy navigation through the pages. Furthermore, it was necessary to devise an appropriate trade-off between the number of levels in the page hierarchy and the content of each page. A table of content style was used here for the start page incorporating icon and text alternatives. The icon bar for navigation was shown on each page at all levels (see Figure 6.10). Scrolling bars were avoided, except for the zoomed map level. Figure 6.10 (a) shows the simple layout of the table of content page with both icon and text. Figures 6.10 (b) and 6.10 (c) illustrate some example pages for text and voice modes of communication respectively, whilst Figures 6.10 (d) (e) and (f) display the area with maps. In detail, Figure 6.10 (d) shows the sketch map of the urban setting U2 with a clickable landmarks list on the right and road name option on the bottom of the page. Figure 6.10 (e) shows the same sketch map on which all the landmarks are displayed, also with the name of the road that was clicked. Figure 6.10 (f) shows a part of the detailed map which was zoomed in from the sketch map page. For the setting U1, the format and style of interface is exactly the same. See Appendix IV for more example pages for both settings. There was a total number of 78 web pages with 39 images created for setting U1, 79 web pages with 41 images for setting U2.

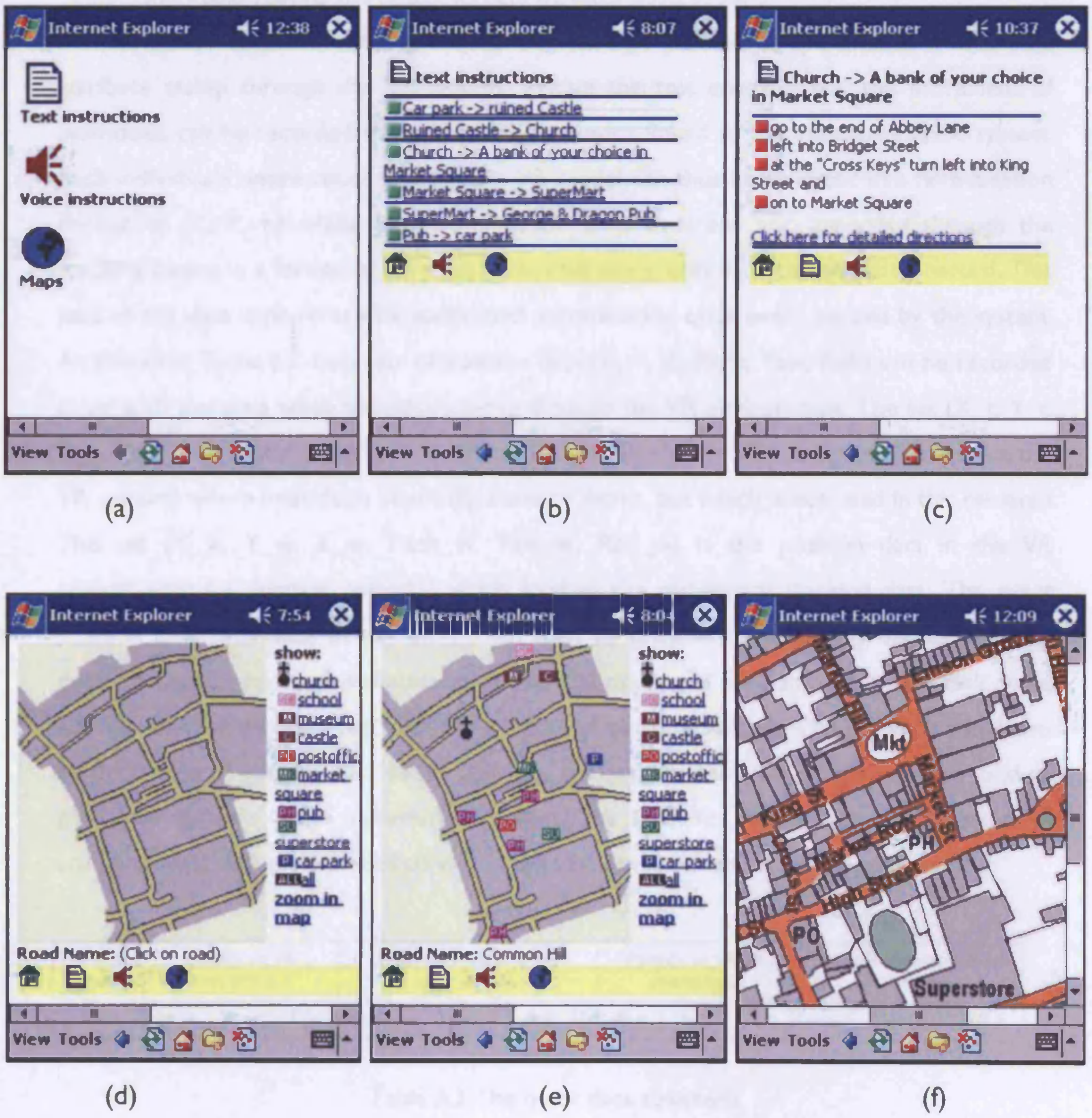


Figure 6.10 Sample pages of information content from the PDA.

6.2.3 Test environment part 3 – multi-source data collection method

The third component of the test environment is a series of software for capturing individuals' interactions and information transactions in completing wayfinding tasks. A multi-source data collection method was established in the test environment which is able to capture and integrate spatio-temporal data of individual position/location within the environment, data on information access via the mobile device and data on individual overt behaviour. This was to ensure that adequate data could be collected with which to analyse the interactions. The data were recorded through a combination of automated and semi-automated means, which included:

- movement tracking data;
- information access and usage data via PDA;
- individual actions and reactions data through observations.

An individual's location within the VR model can be tracked as spatial data with a time attribute stamp through the VR system. Within the test environment, the movement of individuals can be recorded through a tracking device linked to the Intersense IS900 system. Each individual's entire route through the VR model can thus be collected in a time-location format of (X, Y, t,). Head height and head movements are also recorded through the tracking device in a format of (Z, pitch, yaw, roll) along with each time-location record. This part of the data capture can be performed automatically once every second by the system. As shown in Table 6.3, two sets of position data (X, Y, Z, Pitch, Yaw, Roll) can be recorded along with the time when individuals move through the VR environment. The set (X_t, Y_t, Z_t, Pitch_t, Yaw_t, Roll_t) records the actual position in the VR Lab (t denotes 'test' in the VR system) where individuals physically stand or move, but which is not used in this research. The set (X_w, Y_w, Z_w, Pitch_w, Yaw_w, Roll_w) is the position data in the VR environment (w denotes 'world'), which formed the movement tracking data. The exact position of an individual at any time could then be provided through this detailed tracking data. The route that each individual took and the time used for completing each task could subsequently be derived. The time and location of each interaction with the PDA could also be determined from this data set. In addition, the data on head movement could be used to get extra data on when individuals are using the PDA for information and to assist in analysing what individuals are observing in the test environment for future research.

Time in second	Position in VR environment			Head movement in VR environment			Position in VR lab coordinates			Head movement in VR lab coordinates		
Time	X_w	Y_w	Z_w	Pitch_w	Yaw_w	Roll_w	X_t	Y_t	Z_t	Pitch_t	Yaw_t	Roll_t

Table 6.3 The track data structure.

In order to record the information accessed through the PDA and the format in which it is accessed, a set of software was designed and programmed for the PDA. The data on usage of the PDA, can be divided into three main categories: the type of information accessed, the mode of communication used and the time at which the information was accessed. By using a Web browser as the user interface, as discussed in §6.2.2, a set of Cookies was written to record which Web page was being accessed and at what time. Thus, referring to the structuring of the Web pages as previously described (Figure 6.8), it is possible to use the Cookie data files to identify what information was being accessed, at what detail and by which mode. Cookie functions were written using JavaScript and embedded in each Web page. The main function of the Cookies was to record the accessed Web page name, as well as the access time with hour, minute and second. Also when the same Web page was accessed again, the cookie was programmed to capture the time again with a flag showing repeated access. Figure 6.11 shows the structure of a Cookie. Each time that a Web page was activated, a record was written into a corresponding Cookie data file. For establishing a sequential record of the information accessed via the PDA throughout a session in the test environment, the Cookie data files could be combined and sorted by time attribute. This sequential record could also be formed for each individual, showing the progress in wayfinding activity in relation to individual information usages and preferences, for example the most used mode of communication, the level of detail required and the frequency of access. The spatial location of where the information was accessed using the PDA could be derived by integrating the data from the Cookies with the movement tracking data (for details see Chapter 8).

```
function getCookie (name) {
/ retrieve relevant cookie file for write data into it
}

function setCookie(name, value) {
  / save data such as accessed web page name and the access time into cookie file
}

function deleteCookie (name) {
/ delete a cookie
}

function recording (name) {
  / record the name of the Web page and the access time (hour, minute and second)
   when the content of a Web page is accessed first time.
  / record the access time (hour, minute and second) with repeat access flag
  when the content of a Web page is accessed again
}
```

Figure 6.11 The structure of the Cookie.

In addition to these automated measurements, additional data pertaining to participant behaviour was collected through direct observation. These observations included: noting when and where participants got lost or needed to ask for help; the completion time of individual tasks; any rotation of the PDA in the hand (as if turning the map around); and looking at PDA. Participants were encouraged to speak aloud their thoughts and feelings as they progressed through the tasks. Observations of the participants were recorded by the investigator through a semi-automated method using an interface to Access. Using Visual Basic Application (VBA), an observation recording program with a user-interface (Figure 6.12) was programmed with clickable buttons to record observations into an Access database. By clicking a button on the interface, the relevant action stated on the button was recorded into the database table along with the time of recording. This interface was structured around five broad classes of observations. The first group concerned aspects of performance such as start time, task completion, asking for help and so on. Second, there were observations relating to the use of PDA such as looking at it or rotating it. The next two groups concerned details about movement and any apparent confusion and disorientation. Specific movement-related observations included recording whether participants were looking for a street name or specific landmarks. The final group concerned indicators of confidence and any onset of motion sickness (requiring the participant to take a rest). Such motion sickness can affect users of immersive VR. The recorded observation data saved in the Access database files were exported for integrating with other experiment results. Whilst some of these observations entail subjective classification, they nevertheless provide valuable contextual information to supplement automatically collected data and assist in interpreting a participant's overall performance. Because the experiments were carried out in the test environment, recording of observations by the investigator could be more discrete and consistent without interrupting and distracting participants as would likely be the case if carried out in a real world environment.

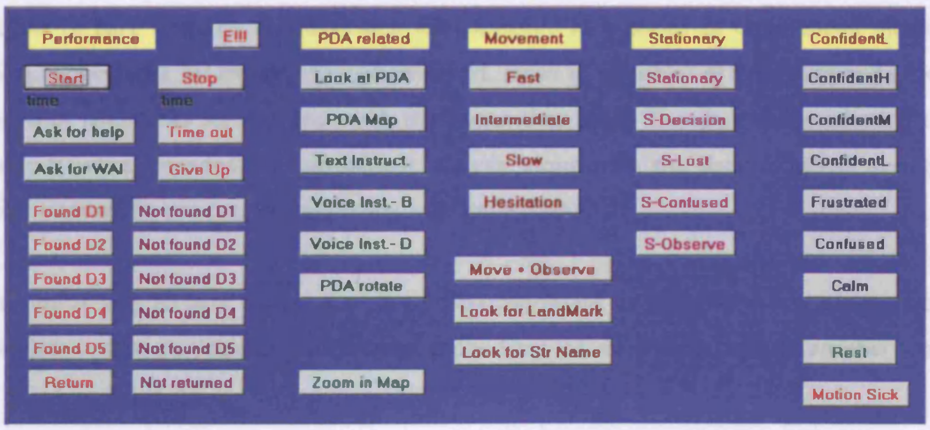


Figure 6.12 The database interface for recording observational data.

By using the multi-source data collection method, the three data sets - movement tracking, information accessed through PDA and participant action and reaction – could be collected automatically and semi-automatically throughout the wayfinding experiments. These data sets together provided facets of a comprehensive picture that could be used to study the behaviour and interaction between individuals, mobile devices and the environment.

6.3 Post-experiment questionnaire

The post-experiment questionnaire was constructed in two parts, in order to assemble data on the feedback from participants following the experiments. The complete questionnaire of part 1 and part 2 are given in Appendix V.

Part 1 of this questionnaire was designed to be carried out by participants immediately following completion of the first set of wayfinding tasks in one of the settings. This part of the questionnaire contained two different sections. Within the first Section, all questions were set up in relation to participant feedback on their experience in the urban VR models, such as their sense of "being there" and their experience in VR urban models in comparison to experiences in real towns. These questions were compiled based upon similar questions used for studying sense of presence in immersive virtual environments (e.g. Usoh *et al.*, 2000; Slater *et al.*, 2002). Importantly, two more questions were specifically created in order to elicit participant feedback on their wayfinding behaviour in VR urban environments. One question concerned whether or not respondents felt that they used a similar manner / approach to find their way in these virtual environments as they did in the real world, whilst another sought to ascertain whether they used similar features to find their way around in these virtual environments as they did in the real world. Each of these questions was designed as structured tick box questions with a six point rating scale from 'strongly agree' to 'strongly disagree'. In addition, two semi-structured questions on the same topic were provided to allow participants to list any specific factors that gave them a sense of 'really being' in the street or that pulled them away from 'really being' in the street. The second Section of part 1 of the questionnaire was designed as a series of open-ended questions, which requested a list of features remembered, recall (if possible) of the route and a sketch map with landmarks for the area with the route they took. The data collected using these methods were intended for subsequent analysis along with the data collected during the actual interaction process in completing wayfinding tasks.

In a similar way to part 1, part 2 of the post-experiment questionnaire was designed to be completed after participants finished the second set of wayfinding tasks in another setting.

The two same questions, as in part 1, about participant feedback on wayfinding behaviour in urban VR environments were used again in order to assess the consistency on this important aspect. Other questions were compiled relating to PDA usage in both wayfinding experiments, such as usefulness of information (maps, text and voice) for wayfinding, and the ease of using the PDA. Also open questions were designed for participants to write down if and why they found the PDA difficult to use if this was the case, what improvement would be useful and what additional information could usefully be provided by the PDA. In the next Section of the post-experiment questionnaire part 2, participants were requested to describe the route taken if they could and to draw a sketch map with landmarks for the area with the route they took. Finally, a short interview was carried out in an informal conversation style. The main purpose of this debriefing interview was to confirm that all questions had been understood and answered. One of the emphases was upon participant feedback on describing their actions and behaviour in VR in comparison with their normal wayfinding behaviour in the real world, particularly with regard to information requirement preferences and strategies adopted in order to complete wayfinding tasks.

6.4 Design of the wayfinding experiments

Having set up the test environment as well as the pre-experiment and post-experiment questionnaires, a wayfinding experiment was designed in order to collect a range of data with the focus on the interaction and information transactions between individuals, devices and environments. The whole wayfinding experiment was designed in four main parts: completing a pre-experiment questionnaire, undergoing a training session, carrying out two sets of wayfinding tasks and completing post-experiment questionnaires along with an informal interview. The pre-experiment questionnaire was set up for participants to complete prior to on-site experiments. The wayfinding experiments were designed for each participant to carry out wayfinding tasks in both urban setting U1 and setting U2. The two settings were modelled in virtual environments as discussed early in §6.2 this Chapter. For the experiments, these two urban models were then implemented in an immersive projection technology VR lab, the CAVE (Cruz-Neira et al., 1993). Post-experiment questionnaires were set up to be completed immediately after each set of wayfinding tasks whilst the informal interview was planned to be conducted after the experiments.

For the two different urban settings, two specific sets of wayfinding tasks were designed. In setting U1, the complete wayfinding task was to begin at a car park and to find five different destinations (a modern church, a post office, a McDonald's, a cinema and a monument) sequentially before returning to the car park as the finishing point (Figure 6.13 (a)). The design for each successive destination of the wayfinding tasks was intended to entail a growing level of complexity in terms of length of route, numbers of turnings, and number of choice points passed. For example, the first wayfinding task was from the car park to the modern church at destination D1 and entailed following a fairly straight road out from the starting point and only contained one obvious turning towards D1. The subsequent tasks were designed to incorporate an increasing number of turnings, junctions and/or roundabouts along the routes. However, in setting U1, the layout of the area was grid-like, therefore some routes in the later tasks might not have appeared to be more difficult than others. To keep the experiment consistent, the set of wayfinding tasks for setting U2 were designed in a similar way. In setting U2, the complete task was also to begin at a car park and to find five different destinations (a castle, St Mary's Church, the Market Square, a superstore and the George & Dragon pub) sequentially before returning to the car park as the finishing point (Figure 6.13 (b)). The wayfinding task for each destination was designed in such a way that the route for reaching each destination would become increasingly complicated. For instance, the first wayfinding task was from the car park as the starting point to the castle as destination D1. The route was a straight road with a left-right choice outside the starting point and two junctions along the route. As for the third wayfinding task from the Market Square D3 to the superstore at destination D4, the route not only contained a number of turnings, but also started at the square with a choice of four roads with which to proceed.

In both wayfinding tasks, all routes selected between two destinations for the text and voice instructions were chosen based on the easiest to follow in comparison with other choices. Also the routes chosen avoided roads already travelled along in order to avoid only a few routes being used during the experiments. These were subjective judgements. The maximum walking speed was set as 4.4 meters per second, slightly faster than normal walking speed. This was tested and arrived at after a number of test runs (see §6.5.3). This was the maximum speed which could be reached by participants. Participants could control the speed up to the maximum or proceed as slowly as they liked. This maximum walking speed was kept the same for both settings.

Figure 6.13 Two urban settings with wayfinding task destinations:
(a) urban setting U1; (b) urban setting U2.

Another important aspect in designing these wayfinding experiments focused upon accessing the information by participants for assisting them in completing tasks. In §6.2.2, the structure and the communication modes used for the information content have been discussed. The information accessed through a PDA can be route instructions (in either text or voice mode) and different levels of map representation. Two options were considered for accessing the information from a PDA: assigning participants into groups before experiments with different restricted information for each group (e.g. a group of participants using route instructions only, whilst another group using maps only); free choice for all participants to choose the type of information they preferred. The first option might result in bias if, for example, text were imposed upon participants with strong preferences for map use or vice verse. Therefore, 'choose information as you prefer' approach was used to explore information preferences during actual wayfinding tasks, instead of assigning participants into groups before the experiments. During the experiments, participants were allowed to choose any information available from the PDA depending on their preference and needs in completing wayfinding tasks. There were no restrictions upon what type of information could be accessed through the PDA and in which communication mode it was conveyed. In addition, no limit was set on the number of times that the information could be accessed.

All participants were treated as a single group to carry out both sets of wayfinding tasks in two urban settings U1 and U2. The approach adopted followed the principle of within-subject design instead of between-subject design (Spector, 1981), although not a strict factorial design. Firstly, with a consideration of idiosyncratic differences between individual participants, particularly on their spatial ability with underlying characteristics such as gender and ethnicity, there would be difficulty in assigning participants into different groups randomly. This would be even more difficult in this research, because the number of participants was not a large sample size because of the limitations of time and resources. These included the budget of using the VR lab and the time of PhD duration. Therefore, both sets of prescribed wayfinding tasks were required to be completed by all participants, one within each of the two different settings assisted by information provided through a PDA. The order of the two settings used in the experiment was alternated according to the concept of counterbalance. Thus half of the participants started their first set of wayfinding tasks in setting U1 and the half started in setting U2, allowing one to offset the other and to be able to study any learning effect.

A number of elements were designed to be held constant in the wayfinding experiment. For the wayfinding tasks in both settings, all the destinations were kept at the same locations and in the same order of completion for all participants. Therefore participants would all visit the same destination locations which would put them on an equal footing to develop their knowledge of the areas. This was further underlined by providing unfamiliar test settings for all participants. Furthermore, a range of information for assisting the wayfinding tasks was provided to all participants. For the last leg of wayfinding tasks in both settings, the experiment was designed in such a way that all participants were provided only with map information (no route instruction available in either text mode or voice mode). The information available for this final task was thus also kept at a constant level. This simulated situation, in which maps were the only available information, could be considered as a control factor in terms of information usage.

The implementation of the entire wayfinding experiment was organised into six sequential sections. The first section entailed a pre-experiment questionnaire (Appendix II), which was required to be completed prior to the on-site experiment. There was also information accompanying the questionnaire explaining the whole experimental procedure, its broad objective, the nature of the experiment VR site and the equipment used. The second section, as a part of the on-site experiment, was a training session before the main experiment that was used in order to familiarise participants with the virtual environment and with the PDA. Following the training session, the third session was a prescribed set of wayfinding tasks to be carried out in either setting U1 or setting U2 (Figure 6.13 (a) and (b)). Post-experiment questionnaire part 1 (Appendix V) was the fourth part of the experiment which was used immediately following the first set of wayfinding tasks. The fifth part was another set of wayfinding tasks that was to be carried out in the alternative setting. As the sixth part of the experiment, post-experiment questionnaire part 2 (Appendix V) was completed along with a short informal interview after participants finished the second set of wayfinding tasks. During the wayfinding experiment, participants were encouraged to speak aloud their thoughts and emotions. The detail of the conduct of the experiment will be discussed in Chapter 7.

6.5 Testing the design

The design and the setting of the experiment were tested in two parts: the questionnaires; and the test environment.

6.5.1 Testing the questionnaires

The principal objective of the pre-experiment questionnaire was to see whether the questions could differentiate different groups of people in term of their spatial abilities. The testing of the questionnaire served as a means of identifying those elements that may need to be modified (see §6.1). The pre-experiment questionnaire was trialled on 89 participants from a wide range of age groups and backgrounds. The participant age ranges were from 18 to over 60. The percentages of respondents in the 30 s age group, 40 s age group and 50 s age group were 14%, 27 % and 6.7% respectively, with 47.2% of them under 30. 40% of respondents were female and 60% male. 50.6% of participants were academics/students from the disciplines of Geography, Surveying, GIS, Planning and Biology. The remaining 49.4% of participants came from a wide range of backgrounds including residents of a town outside London and its surrounding areas, and people working in London and Bristol. For the results from all 21 questions, Ward's (1963) method with Euclidean distance was used to classify participant spatial ability and spatial awareness (see Chapter 8 for details). From Figure 6.14, it is evident that there is considerable linkage distance between three broad groups G1, G2 and G3 regarding the 21 variables (questions). G1 can be interpreted to have low score responses to the questionnaire. G2 have the highest scored responses whilst G3 have better than average scores. A t-test on average scores per question showed significant differences between all three groups ($p < .001$). The analysis of the questionnaires will be discussed in Chapter 8.

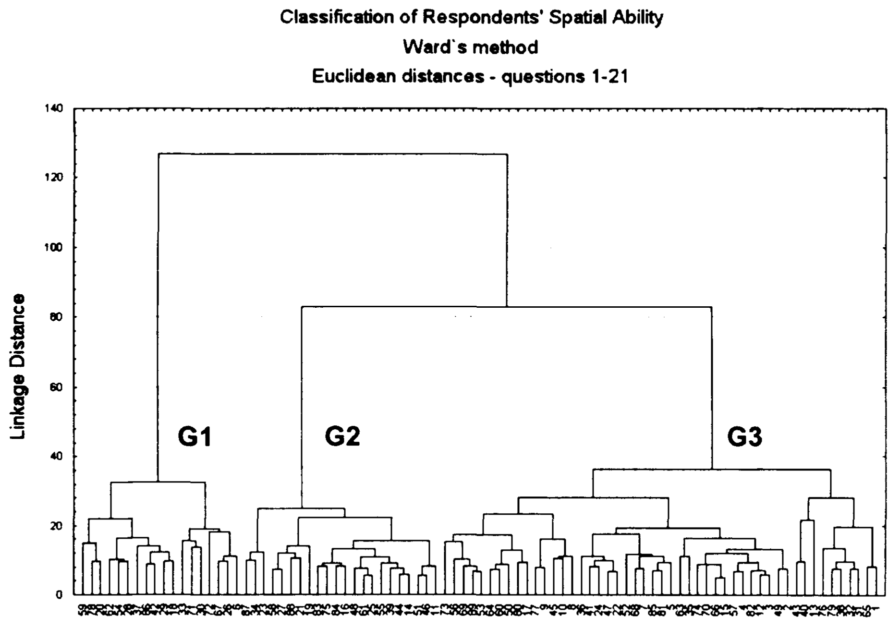


Figure 6.14 Classification tree based on participants' spatial ability using Ward's Method.

The subsequent modifications to the initial questionnaire (Table 6.1) may be summarised as follows. Questions Q4 and Q5 on the sense of direction in aspect A1 were originally set up to ascertain individual thinking about the surrounding environment in terms of cardinal directions: one emphasising a natural open environment, the other emphasising a familiar environment such as their home town. From the results, participants tended to answer both questions in the same way. In addition, the responses showed that these two questions were highly correlated (Spearman's rho 0.68, $p < .001$). Therefore Q4 and Q5 were combined into a single question Q4 (Table 6.2) concerning the general environment. For questions Q6 and Q7, the aim was to differentiate people with preference of image thinking from people with verbal thinking. However, the responses indicated that these two questions were not significantly correlated (as opposed to an expectation of a strong negative correlation). From responses, this could have arisen either because people think they have both image and verbal thinking, or because image thinking could be construed to include images of landmarks and images of maps – thereby giving rise to some confusion. These two questions were therefore deemed ambiguous and were removed. For the Q13 in aspect A7 on map use, the responses showed no distinct differences between participants. The other two questions, Q11 and Q12 in A7 proved better indicators of map use. Therefore, Q13 was removed. Regarding Q16 in aspect A8, over 91% of respondents agreed that there was no confusion between right and left turns and therefore this criterion did not appear to differentiate any characteristic amongst the participants. It may be the case that very few participants did confuse left and right turns. Or perhaps even though people do confuse left and right turns, they tend not to recognise it when answering the question. Nevertheless, Q16 was removed. For testing the post-experiment questionnaire part 1 and part 2, a further nine volunteers took part in completing two sets of wayfinding tasks in the corresponding setting U1 and U2. They completed both parts of the questionnaire after the completion of wayfinding tasks. No difficulty was reported and a short informal interview in a conversation style was found to be welcome and was informative for the investigator. None of these nine participants was included in the wayfinding experiment conducted later because of their acquired experience and knowledge of the urban settings.

6.5.2 Evaluating the test environment

Tests were carried out on the running of the VR models, the functioning of the PDA for providing wayfinding assistance and the functioning of the software for multi-source data collection. The focus of this evaluation was upon the design and technical functioning of the test environment.

With the priority of smooth running of the VR models with natural street views, the first test was carried out to run both models in the VR lab (see §7.3 for detailed description of the laboratory setting) in the Department of Computer Science, UCL. This process was assisted by the lab manager, Dr David Swapp. In the first stage, both models were run only with their object geometry and without their photo-realistic textures. Both object geometry models were found to run smoothly, in their entireties, with a fast response. Therefore, no further generalisation was required on the geometry of the objects. In the second stage, the two models were run with all their photo-realistic textures. For urban setting U2, there were 17.5Mb of image files for texturing. This model did not load successfully. Although the texture memory limit for the SGI machine is 64Mb, the image files, saved as either as jpeg or gif, did not provide a reliable indication of the actual memory space required to present the images. The actual size of the total images used was thus too large to run the model in the system. As a consequence, a set of test trials on reducing the vista range were carried out. With a vista range of 100 metres the model ran smoothly. However, the view in a straight line direction then had only a100 metre vista range and did not appear realistic. With an increased vista range as 200 metres, the model ran smoothly in a straight line, but responded very slowly when encountering more than 45 degree turns: this was not acceptable for the experiment purposes.

Therefore, as discussed in §6.2.1, in order to maintain longer vistas, another option was to systematically reduce the resolution of the photographic images used without seriously compromising the model's realism. A series of test runs was conducted. Firstly, only images with file size less than 100K were included in the model and the performance was found to be smooth. For these, the total file size of texture images was 1.5Mb. Next when the model was tested including all images with file sizes less than 150K, the performance was acceptable. The total size of texture images used was 5.25Mb. According to this guideline, the resolution of the photographic images used for texturing was reduced by a proportional amount on the basis of retaining acceptable visual quality. The number of pixels used in the images was also constrained to a power 2 series in order to optimise the processing speed for the VR system. The model was tested again with these images. It ran smoothly and responded fast, with very similar levels of realism to the full sized images (see Figure 6.15). The total file size of images used for texturing this model was 4.84Mb. The same tests and adjustments were applied to urban setting U1. Here the total file size of images used was reduced from 6.48Mb to 3.62Mb. The performance of the revised model was comparable to that of model U2.

(a)

(b)

Figure 6.15 Reduction of image resolution, an example from setting U2: (a) original image: 738 by 738 pixels; (b) reduced resolution: 256 by 256 pixels

The walking speed in the VR models could be controlled by participants from as slow as they desired up to a maximum of walking speed. The maximum walking speed was initially set as 2.2m per second (7.9 km per hour), which would be considered as a fast walking speed in the real world. Three volunteers were invited to complete the two sets of wayfinding tasks in both urban settings in the VR lab. From the general feedback, the maximum speed was considered to be too slow, and was perceived to be much slower than a walking speed in the real world. This was particularly obvious on long straight stretches of road. As each individual could decide when to reach the set maximum speed and there was no physical tiredness involved, the maximum speed could be increased. As a further consideration, a low maximum speed would cause longer time in the VR lab in completing wayfinding tasks, which could result in more participants suffering from 'motion sickness'. In consideration of such feedback, the maximum speed was therefore doubled to 4.4m per second (10 mph). This maximum speed was tested again. The volunteers were more satisfied with the maximum speed with which they could reach, but still felt it equated to normal walking speed.

Another test on the VR models was to check the consistency of scenes from street viewpoints. Two volunteers, who were both familiar with VR and handling with computers, were invited to inspect exhaustively for consistency of scenes and completion of objects in all models. The two volunteers 'walked' through every street in both urban models and the model for the training session; all models were run on-screen. Every façade of all objects (e.g. buildings) visible from street viewpoints was checked. Any reported façades without realistic photo images were then textured. Furthermore, the consistency of street signs was also inspected, with particular regard to any missing street signs and the consistency of the style. The names on street signs were also checked to make sure that they corresponded to the street names shown on the maps. Improvement was thus made for the final version of the VR models.

The wayfinding assistance provided by a PDA was tested in two aspects: the completeness of the information and any difficulties experienced in PDA use. In the first stage of testing, two volunteers were invited to access all instructions in both text and voice mode via the PDA, and to 'walk' in the VR models (on-screen) following the instructions. The maps were also tested by accessing all options such as zoom-in maps, sketch maps with different landmarks and road names displayed. Any missing and incorrect information was recorded and then amended. There was no report on any difficulty in using the information provided. In the second stage of testing, nine volunteers took part in completing the two sets of wayfinding tasks in both urban settings. The VR models were implemented on a large projected screen instead of in the VR lab as the available grant for using the VR lab could only cover the time for the final experiments. During these tests, the investigator was available to record any problems and feedback given. Any incorrect/missing information was recorded. Further minor modifications were thus made. Regarding the difficulty encountered in using the PDA for accessing the information, it was recorded during the tests and the subsequent interview. Only two concerns were raised in using the PDA: difficulties in using the stylus to click the screen, and the need to use reading glasses coupled with a stronger back light for some individuals. A more clear instruction for using a stylus to click relevant items was then built into the training session. It was also noted in the test procedure that participants should be invited to adjust the back light according to their needs before commencing the experiments.

Finally, tests were carried out on the multi-source data collection method. The recording of location (x, y, z) within the VR models was tested at the same time as three volunteers were tested for walking speed (see above). The tracks, derived from (x, y) coordinates, were plotted and overlaid with the area maps, which were found to precisely represent the routes walked after a simple shift transformation to real world co-ordinates. The z value correctly recorded the eye-level height. The recording frequency was adjusted from once every 0.1 second to once every second to avoid unnecessary large files. For recording the information access and usage via a PDA, the test was carried out while conducting the test for wayfinding assistance information provided on nine volunteers (see the previous paragraph). The data recorded through a set of Cookies were exported from the PDA and sorted by time sequence. The data were then compared with the actual access log recorded by the investigator. The results showed that the set of recordings for this purpose was working correctly. It was noted that there was limited storage capability for each Cookie data file. Therefore, it was decided that the recorded data files would be downloaded when participants took rests during the experiments instead of downloading all data files when the entire experiment was finished. Furthermore, the interface and the program for recording participant action during the wayfinding tasks were tested. The observation data were recorded correctly into the database tables in Access. The interface was improved by re-arranging some of the action buttons for convenience of use. Buttons to record rest periods and the onset of any motion sickness were added to record these events.

CHAPTER SEVEN
Conduct of the Experiments

In this Chapter, the conduct of the wayfinding experiments is described in five sections. It begins with a brief account of the preparatory work carried out for the experiments and is followed by a summary of the participants, a description of the implementation site of the experiments and the equipment used. The conduct of the two sets of wayfinding experiments in two different urban settings is then presented in accordance with the experimental design discussed in Chapter 6. Finally, the procedures of multi-source data capture during the experiment are described.

7.1 Preparation for the experiments

Before conducting the experiment designed for this research, extensive preparatory work was carried out. First of all, an information sheet was written to inform potential participants about the background to the experiments, including the broad objective of the research, the general procedure, as well as the site and equipment used in the experiments. In addition, prospective participants were assured that all of the information provided and collected during the experiments would be treated in strict confidence and that they would not be individually identifiable in the results in any way. Also included in the information sheet was a statement on their right to withdraw from the experiments at any time and without giving any reason. A consent form was prepared for signature by participants in accordance with UCL regulations for using the VR lab. This was to ensure that participants had understood all of the information given, any risk that might occur during the experiments and their right to withdraw. A copy of the information sheet and the consent form can be found in Appendix I. Furthermore, data protection and ethic approval forms were completed by the investigator. Approvals were issued by UCL Records Office and UCL Committee for the Ethics of non-NHS Human Research respectively for recording participant contact data and using the VR lab for experiments.

Having anticipated that the period required to complete the experiments on all participants would last a few months, a procedure and a check list was drawn up for the investigator to ensure that the experimental procedures used for each participant would be consistent. The procedure listed all the steps in the process which should be followed by the investigator before, during and after each experiment. The process steps included preparing for the experiment, such as by ensuring that VR models and equipment were ready, that participants were informed and that correct experiment procedure would be followed in the correct sequence. The check list included all the materials needed for the experiments such as all the questionnaires, task sheets and necessary equipment in the VR lab.

7.2 Participants

The length of each experiment necessitated the use of an opportunity sample of volunteers who were willing to devote the necessary time and effort, often at short notice due the booking constraints of the VR lab. Within this situation, an effort was made to include participants from a range of age groups, different backgrounds and different disciplines. Participants received no payment or any form of incentive for their participation.

A total of 30 participants, who had not been involved in any of the pilot experiments discussed in §6.5, were recruited to take part in the final experiment. There were 14 females and 16 males. One female decided to terminate the experiment after the first task in the first test setting. Another two participants, one male and one female, only completed 5 out the 6 tasks in their first test setting because of motion sickness and VR lab booking time. However, these two participants did complete the part 1 of the post-experiment questionnaire. These two questionnaire responses were included in the analysis in §8.3. The other data collected from these two participants were not included in the data analysis. This reduced the total number of completed participants to 27 with 12 females and 15 males. The mean age of the participants was 33, with ages ranging from 23 to 52 years. Among the full participants, were 12 British and 15 non-British. All but two of the participants (who were visitors with knowledge of UK) were residents of the UK. 20 participants were White (including British White, European White, non-European White) with 7 non-White (including Asian, Orientals and Mixed). For educational background, all participants had a university degree. Participant occupations included university researcher, PhD student, police officer, lecturer, project manager and artist; educational backgrounds included GIScience, geography, planning, computer science, architecture, social science, arts and humanities. All participants had knowledge of using the Internet and searching travel information via the Web, but few of them used a PDA frequently. None of them had previously used a mobile device as a navigation assistant in wayfinding tasks. In addition, none of the participants had any previous familiarity with either of the two urban test settings. A general summary on all participants is shown in Table 7.1 below.

Participants	No.	Males	Females	Average age	British	Non-British
Included in the result data	27	15	12	33	12	15
Excluded (because partially completed tasks)	2	1	1	29	1	1
Excluded (because withdraw from the experiment)	1		1		1	

Table 7.1 Participants characteristics (small number data suppressed).

7.3 Experiment site and equipment

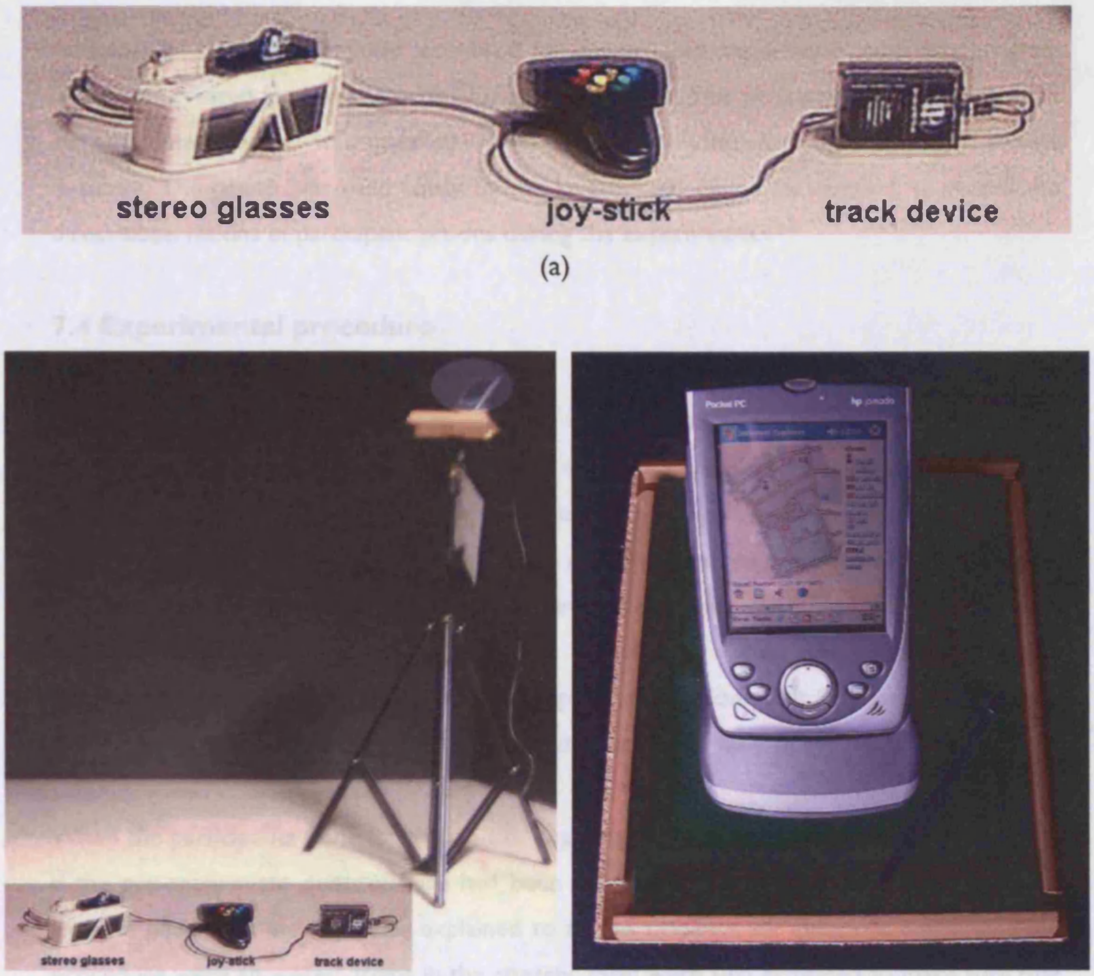
The study areas were two urban areas which had been created as VR models (discussed in §6.2.1), referred to here as urban setting 1 (U1) and urban setting 2 (U2). These covered areas of approximate 48 hectares and 35 hectares respectively. The two urban VR models were implemented in an Immersive Projection Technology (IPT) VR laboratory located in Department of Computer Science at University College London.

This CAVE-like IPT system was used to generate the virtual environment for the experiments. It was powered by a Silicon Graphics Onyx2 with eight 300MHz R12000 MIPS processors, 8GB RAM and four Infinite Reality2 graphics pipes (Swapp, 2004). This machine processed all the graphics input pertaining to the system. The images were projected onto three 3 metre by 2.2 metre walls (front, left and right wall) and a 3 metre by 3 metre floor (Figure 7.1 (a) and (b)). Participants wore CrystalEyes stereo glasses during the experiments. The stereo glasses incorporate tracking devices (Figure 7.2 (a)) that can record participant locations using an Intersense IS9000 system with 2mm accuracy, with an end-to-end latency of 50ms. The IPT system runs at a maximum refresh rate of 45Hz in stereo. In this experiment, participant locations within the VR models were recorded once every second with 0.1m accuracy. In addition, a joy-stick like device was used to control movement in the VR environments, as shown in Figure 7.2 (a). Although participants could physically move in the 9 square metres of VR laboratory space during the experiments, the 'walking' and 'moving around' in the VR environments were actually controlled by using the joy-stick device. In the VR test environments, participants could turn their head to the left or to the right in order to view the surrounding environments. The view was not restricted to a narrow angle. Figure 7.1(a) illustrates a close-up view of a participant navigating using a joy-stick device in test urban setting 1 (U1) with projected images on the floor and the walls of the VR laboratory, whilst Figure 7.1(b) shows a more general scene with a participant in test urban setting 2 (U2) with projected images on the three walls and the floor. Other scenes from both urban settings are given in Appendix III.

(a)

(b)

Figure 7.1 Scenes of the experiment settings in the VR laboratory; the PDA can be seen on top of the tripod to the right in (b).



(a) (b) (c)

Figure 7.2 Elements of equipment used in the experiments:

(a) stereo glasses, joystick and track device; (b) a general view of the equipment in the CAVE; (c) the PDA placed on a small platform.

Another set of equipment used in the experiments comprised a Personal Data Assistant (PDA) and a tripod with a small platform for placing the PDA (Figure 7.2(b) and Figure 7.2(c)). The model of the PDA was an HP Jornada 568 (donated by Hewlett Packard Labs, Bristol) with a 240 by 360 pixels screen and 63.32MB ARM SA1110 processor. A stylus was used to activate programmes or to select items by tapping the screen. The information for assisting wayfinding could be accessed through the PDA using a standard Internet Explorer interface. In addition, a small platform with a wooden edge and felt surface was specially made for the experiments, shown in Figure 7.2 (c). This small platform fixed on top of a height adjustable tripod allowed participants to easily place the PDA within reach (Figure 7.2 (b)). This was done to reduce the inconvenience that participants might feel since they would have to hold the joy-stick during the wayfinding tasks.

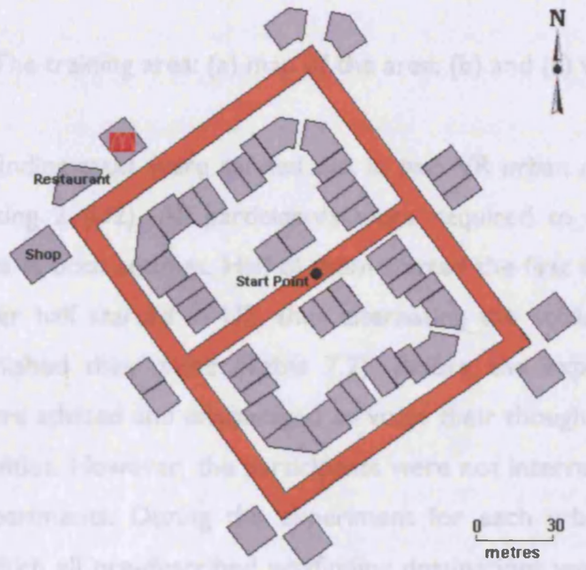
Additionally, a laptop computer was used for running the observation recording program which was created for this research (discussed in §6.2.3). This program used a purpose-built clickable interface and was installed in the laptop as an interface to a Microsoft Access database. The laptop was used solely by the investigator, in the background, to record the direct observations of participant actions during the experiments.

7.4 Experimental procedure

Prior to the on-site experiments, an email or a printed letter was sent out to all recruited participants. Provided in the email/letter was the information sheet and the consent form discussed in §7.1. The pre-experiment questionnaire (see §6.1 and Appendix I) was also attached with the email/letter. All participants were required to complete the questionnaire before the experiments, and to bring the completed questionnaire and the consent form with them when attending the experiments. In addition, a map was included giving the location of University College London and Department of Computer Science building where the VR Lab is located, together with a written instruction on how to get the VR Lab.

When the participants came for the on-site experiments, the investigator checked with them if the pre-experiment questionnaire had been completed. Then the experiment procedure and the equipment were further explained to the participants. All questions concerning the procedure were answered. Items in the consent form were also explained to make sure that the participants fully understood their right to withdrawn from the experiment and the possible potential risks (e.g. motion sickness) caused by using VR environments. No information was given on the real towns upon which the VR urban models had been based. All participants were satisfied with the information provided about the experiments. The consent form was signed by all participants. This process took approximately five to ten minutes.

At the beginning of the wayfinding experiments, a training session was provided to all participants inside the VR environment. Figure 7.3 (a) shows the map of the training area, whilst Figure 7.3 (b) and (c) shows two views of it. One aspect of the training session was to familiarise the participants with navigating in a VR environment. The participants, wearing a pair of stereo glasses, were shown how to use the joystick to 'walk' around inside the VR training area. They were informed that they could move their head left or right / up or down to view the surroundings as in the real world. They were also informed that they could physically move around in the 3m by 3m lab floor area, but that the movement in the VR environment was controlled by the joystick. In addition, all participants were advised to 'walk' along the road network, rather than roam amongst the buildings or across the lawns which would be parts of residents' garden areas. The participants were then allowed to practice navigating inside the VR training area for approximately 5 minutes. Another aspect of the training session was to instruct the participants on how to access the information using a PDA when attempting the wayfinding tasks. All options were shown to the participants for acquiring maps, text and voice information; and they were informed that they could choose any available information from the PDA during the experiments, at any time according to their preference and needs in completing the wayfinding tasks. The participants were given about a further 5 minutes to practice. The total training session took approximately 15 minutes.



(a)

(b)

(c)

Figure 7.3 The training area: (a) map of the area; (b) and (c) views of the training area.

The main wayfinding tasks were carried out in two VR urban models: urban setting 1 (U1) and urban setting 2 (U2). All participants were required to complete the pre-described wayfinding tasks in both settings. Half of them started the first set of wayfinding tasks in U1, whilst the other half started in U2, thus alternating the setting in which the participants started and finished their tasks (Table 7.2). Before the experiments were started, the participants were advised and encouraged to voice their thoughts and emotions during their wayfinding activities. However, the participants were not interrupted or reminded to do this during the experiments. During the experiment for each urban setting, an A4 page was provided on which all pre-described wayfinding destinations were printed in sequence. This paper, which was fixed on the top of the tripod, can be seen in Figure 7.2 (b). No required time limit was set for the participants to finish the wayfinding tasks.

The urban setting used for the first part of wayfinding tasks	Participants
Urban setting 1 (U1)	P01, P03, P05, P07, P09, P11, P13 P15, P17, P19, P21, P23, P25, P27
Urban setting 2 (U2)	P02, P04, P06, P08, P10, P12, P14 P16, P18, P20, P22, P24, P26

Table 7.2 Sequence of urban settings used for each of the participants.

The process of conducting the experiments followed the designed wayfinding experiment procedure as discussed in §6.4. For the first set of wayfinding tasks, all participants were instructed to begin at a car park (marked P in Figure 6.12 (a) and (b)) as the starting point and to then find five destinations D1 to D5 sequentially before returning to the car park (see Table 7.3). Figure 7.4 (a) to (f) and Figure 7.5 (a) to (f) show scenes of the start/finish point and five destinations D1 to D5 in both VR urban settings U1 and U2 respectively. The participants were advised to take rests either at any one of the destinations or any other time when they felt this was needed. During the experiments the participant's exact current position was not displayed on the PDA. The reasons for this are twofold. Firstly, in the real world, although the location of individuals can be identified through location-aware mobile devices, this would be to different levels of accuracy depending on the positioning technologies used (GPS, cellular network based) and the nature of the urban area (high-rise city centre, low-rise suburban). Hence, given current technologies, the location of a mobile device cannot accurately and consistently be expressed as a point in urban areas. Secondly, not providing exact current position puts all participants on an equal footing regardless of whether maps, voice or text are used. However, the starting point could be clearly identified by participants. No participants had problems in locating the start points in settings U1 and U2. During the experiment, all participants used the PDA to access information (route instructions and/or maps of the area) for assisting their wayfinding activities. Of the 30 participants that took part in the first set of wayfinding tasks, 27 completed all of the pre-specified tasks. Among the three participants who did not complete the tasks, one decided to withdraw from the experiment after reaching the first destination D1 in setting U1. This participant did not feel very well yet still wanted to carry on. Later, this participant was advised to stop. The other two participants that did not complete the tasks stopped at destination D5 (one in setting U1 whilst another in setting U2) after finished five wayfinding destinations. Both were ended due to motion sickness caused by navigating in VR. The time taken for completing the first set of wayfinding tasks varied depending on each participant's situation, ranging from 40 minutes to 1 hour. This also included time taken for rests. The post-experiment questionnaire part 1 (discussed in §6.3, see also Appendix V) was given to each participant after he/she finished the first set of wayfinding tasks whether in setting U1 or U2. Participants were led to an adjacent room in order to finish the questionnaire and the investigator was on hand to answer any questions that they might have about the questionnaire. The time for completing the post-experiment questionnaire part 1 was approximately 15 minutes.

	Destinations in U1	Destinations in U2
start	**P** - car park	**P** - car park
D1	✝ - modern church	Castle
D2	**PO** – Post Office	✝ - Church
D3	MacDonald's	**Mkt** - Market Square
D4	Cinema	Superstore
D5	Monument	**Pub** – public house
finish	**P** - car park	**P** - car park

Table 7.3 The destinations in urban settings U1 and U2.

(a)


(b)

(c)

(d)

(e)

(f)

Figure 7.4 The scenes at the starting point and five destinations in setting U1: (a) the start/finish point; (b) destination D1; (c) destination D2; (d) destination D3; (e) destination D4; (f) destination D5.

(a)

(b)

(c)

(d)

(e)

(f)

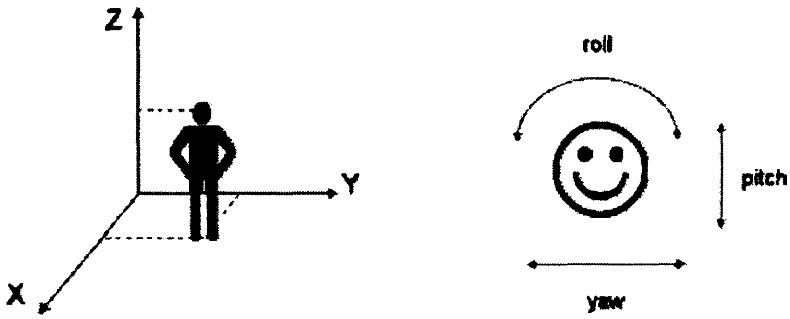
Figure 7.5 The scenes at the starting point and five destinations in setting U2: (a) the start/finish point; (b) destination D1; (c) destination D2; (d) destination D3; (e) destination D4; (f) destination D5.

The procedure for the second set of wayfinding tasks was carried out in the same way as the first, except that it was performed in a different test setting. The 27 participants, who finished the first set of wayfinding tasks, had all completed the wayfinding tasks in the other setting. The time taken ranged from 40 minutes to 1 hour, which also varied from person to person. The post-experiment questionnaire part 2 (Appendix V) was then completed in a similar manner to part 1 by the participants, which took approximately 15 minutes. An approximate five minute informal de-briefing interview was conducted in a conversation style and minuted on paper afterwards by the investigator. The entire on-site experiments took about 2 -3 hours to complete for each participant.

7.5 Data capture

Data were captured during the experiment automatically and semi-automatically using different devices. These multi-source data were the positional track through the VR systems, the PDA usage data via cookie files and the observation data recorded by using an Access database with a purpose-built clickable interface.

During the course of the wayfinding experiments, the location of each participant within each urban setting was tracked with a time stamp using the tracking device and the VR system. The VR system was run and monitored by the CAVE manager during the experiments. The entire route of each participant was recorded in a time-location format of (t, x, y). Head height and head movements were also logged in a format of (z, pitch, yaw, roll). Figure 7.6 (a) illustrates the positional data, whilst Figures 7.6 (b) demonstrates the head movements. These data were captured automatically once every second and saved in text files. A sample of the track data is shown in Table 7.4. The six columns (X_w, Y_w, Z_w, Pitch_w, Yaw_w, Roll_w) are the position data in the VR environment, which include x y z coordinates and head movements. The following six columns (X_t, Y_t, Z_t, Pitch_t, Yaw_t, Roll_t) record the actual position data in VR Lab where individuals physically stand or move, which is not used in this research.



(a) (b)

Figure 7.6 Positional data (X, Y, Z) and head movements (Pitch, Roll, Yaw): (a) positional data; (b) head movement.

Time	X_w	Y_w	Z_w	Pitch_w	Roll_w	Yaw_w	X_t	Y_t	Z_t	Pitch_t	Roll_t	Yaw_t
791.0:	58.4	211.6	1.6	-10.6	8.4	45.0	0.5	-0.7	1.5	-10.6	8.4	-12.2
792.0:	58.4	211.5	1.6	-10.6	8.4	32.6	0.5	-0.7	1.5	-10.6	8.4	-12.2
793.1:	58.2	211.7	1.6	-10.4	8.7	30.8	0.5	-0.7	1.5	-10.4	8.7	-10.7
794.0:	57.2	212.7	1.6	-10.2	8.9	32.4	0.5	-0.7	1.5	-10.2	8.9	-9.1
795.0:	56.0	213.7	1.6	-10.9	7.8	27.1	0.5	-0.7	1.5	-10.9	7.8	-14.3
796.0:	54.9	214.8	1.6	-9.5	10.7	39.3	0.5	-0.7	1.5	-9.5	10.7	-2.1
797.0:	53.8	215.8	1.6	-9.5	11.0	41.7	0.5	-0.7	1.5	-9.5	11.0	0.3
798.1:	52.6	216.8	1.6	-10.4	10.2	36.3	0.5	-0.7	1.5	-10.4	10.2	-3.8
799.0:	52.2	217.3	1.6	-10.5	10.1	26.2	0.5	-0.7	1.5	-10.5	10.1	-4.4
800.0:	51.6	218.0	1.6	-10.0	9.2	31.0	0.5	-0.6	1.5	-10.0	9.2	0.5
801.0:	50.8	219.3	1.6	-10.7	9.1	31.7	0.5	-0.6	1.5	-10.7	9.1	1.2
802.0:	49.9	220.4	1.6	-7.3	9.6	36.6	0.5	-0.7	1.5	-7.3	9.6	6.1
803.1:	49.0	221.7	1.6	-8.9	9.2	34.7	0.5	-0.7	1.5	-8.9	9.2	4.1
804.0:	48.5	222.4	1.5	-39.7	10.3	37.8	0.5	-0.6	1.4	-39.7	10.3	7.2
805.0:	48.2	222.8	1.6	-6.9	7.7	36.3	0.5	-0.7	1.5	-6.9	7.7	5.7
806.1:	47.3	224.2	1.6	-8.9	7.7	36.5	0.5	-0.7	1.5	-8.9	7.7	5.9
807.0:	46.5	225.4	1.6	-8.9	7.7	36.5	0.5	-0.7	1.5	-8.9	7.7	5.9

Table 7.4 Sample data from of the movement track data.

The second set of data captured during the experiment was PDA usage. On each occasion that participants used the PDA to acquire information, the pages accessed along with the access time were recorded automatically through the programmed Cookies. A sample of the recorded Cookie data files is shown in Figure 7.7. The first line is the name of the information page that was accessed; and the second line is the time when it was accessed. The subsequent lines record the file directory in which the page was stored and the system expiring time. After the '*' sign, there is another record showing that the same page was accessed again. For the record shown in Figure 7.7, a sketch map page with all landmarks shown (SW-SALL) was accessed twice, once at 16:45:55 and another time at 16:55:10.

```
SW-SALL
16M45S55
~~local~~/\sw-pda\sw-sall\
0
127716556831079292728775552296451 13
*
16M55S10
V
~~local~~/\sw-pda\sw-sall\
0
127716556831079292198380825629645114
*
```

Figure 7.7 Sample data from Cookie data files.

Additional observations for each participant's actions were carried out by the investigator throughout the experiment. These observations were recorded by clicking the relevant action buttons through the observation recording program interface (Figure 6.11). These observations included when participants looked at the PDA for information, where participants got lost, the completion time of individual tasks, any rotation of the PDA in the hand (as if turning the map around) and so on. Participants were encouraged to speak aloud their thoughts and feelings as they progressed through the tasks. Thus, some observations on emotion and the confidence level of participants during the wayfinding tasks could also captured. Figure 7.8 illustrates a part of a recorded observation data table in an Access database file. The action column corresponds to the option buttons in the interface, whilst the time was captured automatically when buttons were clicked.

count	action	time
33	Found D2	25/08/2004 11:43:12
34	Stationary	25/08/2004 11:43:53
35	Look at PDA	25/08/2004 11:43:54
36	Voice Inst.- B	25/08/2004 11:43:57
37	Slow	25/08/2004 11:44:06
38	ConfidentM	25/08/2004 11:44:28
39	Intermediate	25/08/2004 11:44:29
40	Look for Str Name	25/08/2004 11:44:51
41	Intermediate	25/08/2004 11:44:52
42	S-Lost	25/08/2004 11:45:04
43	Look for Str Name	25/08/2004 11:45:08
44	Look for Str Name	25/08/2004 11:45:14
45	Stationary	25/08/2004 11:45:16
46	Look at PDA	25/08/2004 11:45:17

Figure 7.8 Sample data from recorded observation data files.

Throughout the experiments, the multi-source data were captured, including the positional track data, information usage data and observation data. The data could then be synchronised and integrated. The exact position of an individual in VR urban settings at any time could thus be re-traced through the detailed tracking data. Furthermore, the information usage data and observation data could subsequently be explored along with the location and time.

7.6 Conclusion

The final wayfinding experiments including the pre-experiment questionnaire and post-experiment questionnaire and debrief interview were carried out successfully following the designed procedure. A wide range of empirical data was collected through the experiments. In the next Chapter, these data are discussed in detail and analysed.

CHAPTER EIGHT
Data Integration, Analysis and Discussion

As discussed in Chapter 7, data have been collected through a range of different data sources. There are four principal data sets that have been created by this research: movement tracking, information accessed through a PDA, observation data of participant actions and data from questionnaires. The integrated data and derived variables together provide elements of a comprehensive picture that can be used to study the behaviour, interaction and spatial information transactions between individuals, mobile devices and environments. Formatting and integrating the original data collected from the experiments is described in §8.1. The pre-experiment questionnaire is analysed in §8.2, whilst the questions relating to sense of presence in VR and the commonality of wayfinding strategies in VR and the real world in the post-experiment questionnaire are examined in §8.3. In §8.4 position, distance and time variables are analysed in terms of wayfinding behaviour. PDA spatial information usage is analysed in §8.5 and a classification of individual patterns of PDA usage is presented in §8.6. In §8.7 a number of group and individual case studies are provided.

8.1 Data Formatting and Integration

Data from the experiment results were collected through four different data sources: positional data tracked through the VR system, PDA spatial information usage data captured through the Cookies written and installed in the PDA (§6.2.3), observation data of participant actions recorded through an Access database with an interface programmed and installed in a laptop (§6.2.3), self-assessed individual spatial ability measures obtained through the pre-experiment questionnaire (§6.1 and Appendix II) and feedback to the experiments in the post-experiment questionnaires (§6.3 and Appendix V). These original data can then be categorised as follows:

- positional data with time showing the movement track of each participant: $P_i(t, x, y)$ along with head height data z and head movement data pitch, yaw and roll, as discussed in §7.5;
- PDA information usage: Info-PDA$_i$ $\{t, P_{type}, P_{mode}, P_{access}\}$ which are respectively the type of information acquired from the PDA (e.g. map information, route information), the mode by which it was acquired (e.g. through voice, text or map layout) and the way in which it was accessed (either click for new information or look again at the same information);

- observational data: $O_i\{t, B_{PDA}, B_{tcomplete}, B_{move}, B_{confidence}\}$ which are respectively the usage of PDA (such as rotation of the device and looking at PDA), the completion of individual tasks, movement characteristics (e.g. looking for street name, hesitation or making decision), and the level of confidence expressed during the wayfinding tasks;
- response data from the pre-experiment questionnaire on participant self-assessed spatial ability $SA_i\{S_{sd}, S_{mu}, S_{gsa}, S_{sa}\}$ which respectively represent the self-assessed sense of direction, map use, general spatial ability and spatial awareness (the details of these four aspects are discussed in §6.1 and §6.5.1); $TK_i\{TK_{route}, TK_{landmark}, TK_{map}\}$ presents individual tendency for route-oriented, landmark-oriented and map-oriented thinking in wayfinding, visual-spatial ability and technology familiarity;
- feedback data from post-experiment questionnaires on the experience of VR with respect to 'sense of presence', and commonality between wayfinding approaches adopted in VR environments and those used in the real world;
- sketch maps of the settings and written descriptions of the routes taken;

where i = 1 to 27 for each participant; *t* is the time recorded in seconds.

8.1.1 Formatting of the Original Data Sets

The positional track data record the movement of each participant, $P_i(t_i, x_i, y_i)$ i = 1 to 27. The (x, y) coordinates recorded through the VR system were not in the GB National Grid coordinate system. Following the principle of geo-rectification commonly used for satellite imagery, coordinates recorded through the VR system were compared with the coordinates in the GB National Grid system for shift, rotation and scaling in order to transform the original track data to the National Grid. No scaling and rotation was needed to position data in both settings U1 and U2. Only shift was required:

- $X_i = x_i + 485{,}273$, $Y_i = y_i + 237{,}528$ for setting U1
- $X_i = x_i + 553{,}831$, $Y_i = y_i + 238{,}435$ for setting U2

The track data, therefore, can be overlaid with OS MasterMap™ data. Data on head height z and head movement (pitch, yaw, roll) are not used for analysis in this thesis, and are only used to confirm observation data such as whether an individual was looking at the PDA or looking at street names. Thus no formatting has been carried out on these data. Furthermore, according to the observation records of resting time for each participant, the position data recorded by the VR system during these rest times were removed. Finally, for the positional track data, 54 data tables were created using time as index field covering all 27 participants in both settings U1 (total 43,985 positional track points) and U2 (total 44,156 positional track points).

PDA information usage data were recorded through Cookies installed in a PDA. There are 1132 recorded Cookie text files for the 27 participants, 463 files for setting U1 and 670 for setting U2. Scripts were written to extract, from these text files, the data on PDA information accessed and the access time, and to join all the records for each participant into a data table with time as the index field. Thus PDA information usage data were in 54 data tables comprising 27 tables for U1 and 27 tables for U2.

Participant overt actions were recorded through observation during the experiments. These were stored in Access database tables with time as the index field. These data tables were exported into 54 observation data tables which are for 27 participants in both settings U1 and U2.

For the pre-experiment questionnaire (§6.1 and Appendix II), responses to questions 1 to 17 were coded into numeric 0, 2, 4, 6, 8 and 10 representing answers from 'strongly disagree' to 'strongly agree'. The responses to questions 18 to 22 relating to familiarity with technologies were coded as 0, 2, 4, 6, 8 representing answers from 'never' used to 'daily' or 'weekly' usage. A spreadsheet was created for all 27 participants with all coded responses for all 22 questions along with participant demographic background. The last two questions were coded as descriptions in text format. The responses to the visio-spatial ability test were scored as the number of correct answers.

Feedback from the post-experiment questionnaire (§6.3 and Appendix V) was also coded into a spreadsheet. The responses to the first 6 questions concerning the experience after wayfinding in VR environment were coded as 0, 2, 4, 6, 8 and 10 representing answers from 'strongly disagree' to 'strongly agree'. The next 2 questions, which are descriptions of the experience in VR, were coded in text format. In addition, the features remembered and the description of routes taken were coded as descriptions in text format. Sketch maps drawn by each participant were also coded with scanned image and explanatory text with participant ID attached.

In all the above data sets, participant ID numbers were used as references for each individual and all names were removed from the data sets.

8.1.2 Data Integration

The data sets discussed above can be integrated to provide a data source containing a range of elements which permit the study of behaviour and interactions between individuals, mobile devices and environments. There were three stages for integrating these data sets. Firstly, the PDA information usage data sets and observation data sets for each participant were combined and sorted sequentially through the time field *t* in both data sets to form a time series. This process was carried out for all 54 tables covering 27 participants in both settings U1 and U2. Thus 54 actions tables were created comprising both PDA information usage and observed overt actions in a time sequence. Secondly, these action data tables were joined with positional track tables using common time field *t* as the primary key in both data sets. Thus geographical coordinates were added to the PDA information usage data and the observation data. This integration was performed on the 54 action tables and 54 positional track data tables. Thirdly, these data were further linked with individual spatial ability elicited from pre-experiment questionnaire data, using participant ID as a primary key. Responses from the post-experiment questionnaires were also linked with these data in the same way. Figure 8.1 illustrates these stages of the data integration.

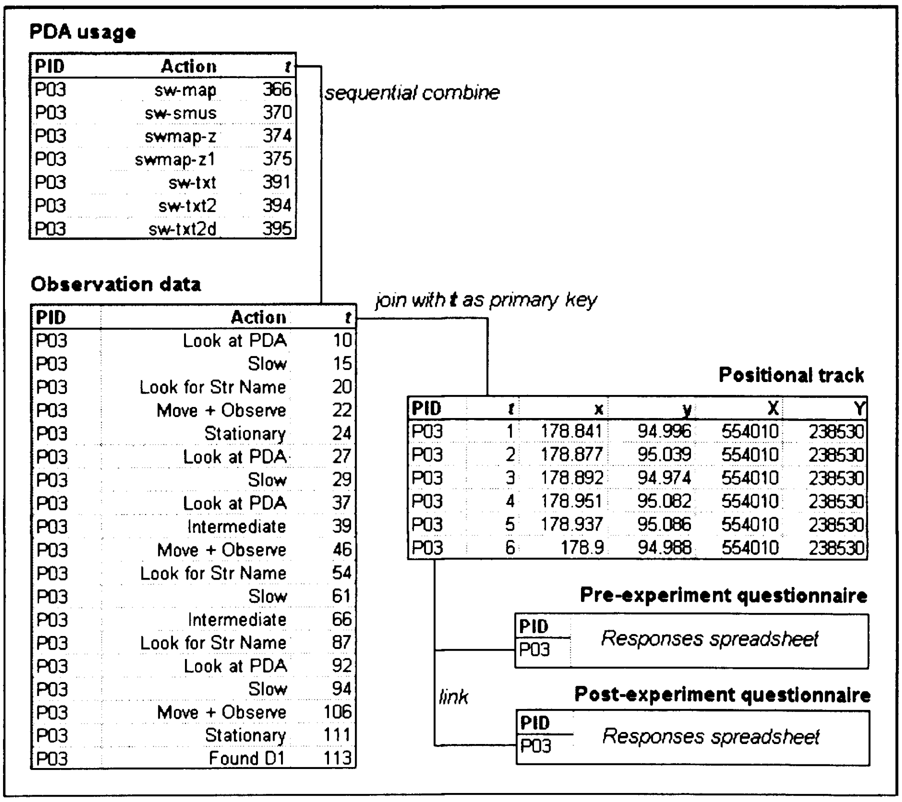


Figure 8.1 The data integration process

Through integrating the different data sets, additional variables could be calculated such as completion time, distance travelled, route taken, when and where information was required, when and where errors occurred. Additionally, individual and aggregated routes could be mapped and studied. Thus, the integrated data set was able to capture many pertinent aspects of information usage, overt actions, wayfinding performance, and an indication of user preferences. Table 8.1 provides an example of the finished integrated data table including some additionally calculated variables.

Ref	PID	Lapse	X	Y	Action	PDAuse	PDAelapse	Time4task	route	Distance	static-time	PDA-timeT	Plan-time
43646	P03	983	553923	238343					5	1.41	PDAuse	PDA-routeT	planning
43647	P03	984	553923	238343					5	0	PDAuse	PDA-routeT	planning
43648	P03	985	553923	238343					5	0	PDAuse	PDA-routeT	planning
43649	P03	986	553921	238344					5	2.24	PDAuse	PDA-routeT	planning
43650	P03	987	553921	238344					5	0	PDAuse	PDA-routeT	planning
43651	P03	988	553921	238344					5	0	PDAuse	PDA-routeT	planning
43652	P03	989	553921	238344					5	0	PDAuse	PDA-routeT	planning
43653	P03	990	553921	238344	Move + Observe			52	5	0	PDAuse	PDA-routeT	planning
43654	P03	991	553921	238344	Look at PDA	PDA-txt-look	23	53	5	0	PDAuse	PDA-routeT	planning
43655	P03	992	553921	238344					5	0	PDAuse	PDA-routeT	planning
43656	P03	993	553921	238344					5	0	PDAuse	PDA-routeT	planning
43657	P03	994	553921	238344	sw-map	PDA-mapS-click	3	56	5	0	PDAuse	PDA-mapS	planning
43658	P03	995	553921	238344					5	0	PDAuse	PDA-mapS	planning
43659	P03	996	553921	238344					5	0	PDAuse	PDA-mapS	planning
43660	P03	997	553921	238344					5	0	PDAuse	PDA-mapS	planning
43661	P03	998	553921	238344					5	0	PDAuse	PDA-mapS	planning
43662	P03	999	553921	238344					5	0	PDAuse	PDA-mapS	planning
43663	P03	1000	553921	238344	sw-sall	PDA-mapS-click-lmk	6	62	5	0	PDAuse	PDA-mapS	planning
43664	P03	1001	553921	238344					5	0	PDAuse	PDA-mapS	planning
43665	P03	1002	553921	238344					5	0	PDAuse	PDA-mapS	planning
43666	P03	1003	553921	238344	sw-rdelmsa	PDA-mapS-click-strn	3	65	5	0	PDAuse	PDA-mapS	planning

Figure 8.1 Example of integrated data table.

8.2 Analysis of Pre-Experiment Questionnaire

8.2.1 Variables

Four variables indicating individual spatial ability have been derived from the results of the pre-experiment questionnaire. The first variable, denoted as S_{sd} in this thesis, concerns the sense of direction aspect of spatial ability. The initial value of variable S_{sd} for each participant is their combined total score for questions Q1 to Q5 in Table 6.2. The second variable, S_{mu}, reflects map use ability with its initial value as the combined total score of questions Q9 and Q10 in Table 6.2. General spatial ability as the third variable, denoted as S_{gsa}, concerns people's ability performing spatial tasks related to wayfinding in life. The initial value of S_{gsa} is the combined total score of questions Q11 to Q14 in Table 6.2. The fourth variable, S_{sa}, reflects people's spatial awareness with its initial value as the combined total score of questions Q15 to Q17 in Table 6.2. All the above combined scores are with equal weighting. Therefore, individual spatial ability can be expressed as $SA_i\{S_{sd}(i), S_{mu}(i), S_{gsa}(i), S_{sa}(i)\}$ with i = 1 to 27 from the responses to the questionnaire. Because of the different number of questions included in each of these four aspects, the final value for each composite indicator was the initial value of combined total scores divided by the corresponding number of questions in each aspect, in order that the four variables can be represented on the same scale (0, 10). Table 8.2 shows these four variables for each participant.

	S_{sd}	S_{mu}	S_{gsa}	S_{sa}
P02	7.6	8	9.5	8.7
P03	8	9	6	8.7
P04	6.4	10	8	10
P05	3.6	6	2	4
P06	3.6	6	3	6.7
P07	8	6	7	7.3
P08	3.6	10	1	8
P09	8	10	8.5	8.7
P11	6.8	9	7.5	9.3
P12	8.4	10	8	10
P13	3.6	7	7.5	8
P14	8.4	10	8	9.3
P15	6.8	10	7	8
P16	6.4	7	7.5	8
P17	4.4	6	4	5.3
P18	3.6	7	4	5.3
P19	4	3	2.5	5.3
P20	6	10	6	7.3
P21	4	8	4.5	7.3
P22	6.4	7	4.5	4
P23	6.4	8	6	7.3
P24	5.6	10	4	8
P25	5.6	7	5.5	7.3
P26	8.8	9	6.5	8
P27	5.6	7	5	7.3
P29	6.4	10	5.5	10
P30	6	9	5.5	8

Table 8.2 Four composite variables indicating individual spatial ability.

The next set of variables $\{TK_{route}(i), TK_{landmark}(i), TK_{map}(i)\}$ where i = 1 to 27, indicate individual tendency for route, landmark and map thinking during wayfinding. These were derived from the responses to Q6, Q7 and Q8 in the pre-experiment questionnaire (Table 6.2). As shown in Figure 8.2 a higher proportion of the participants reported that they tend to have landmark-orientated thinking while carrying out wayfinding tasks in comparison with route-oriented or map-oriented thinking. In addition, participants showed that route-oriented, landmark-oriented and map-oriented thinking are not mutually exclusive to each other. These three variables $\{TK_{route}, TK_{landmark}, TK_{map}\}$ will be further analysed in the next Section.

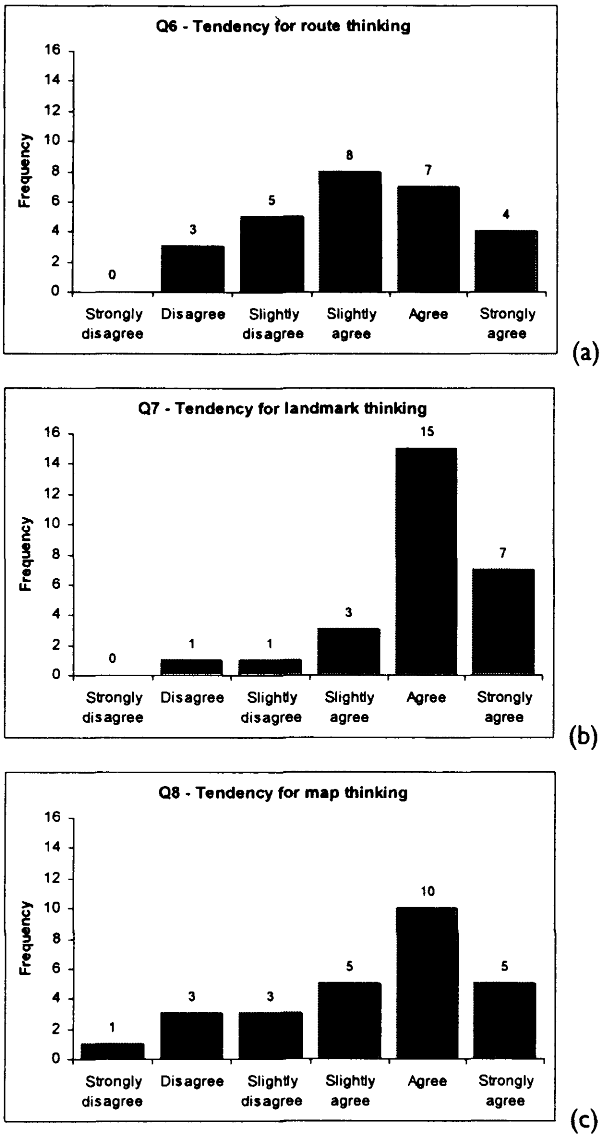


Figure 8.2 Bar charts of the responses to questions: (a) Q6; (b) Q7; (c) Q8.

The responses for the next part of the pre-experiment questionnaire give an indication of individual's usage of related technologies (Table 6.2). Through these questions (see Appendix II) it is possible to detect variations amongst the selected participants in terms of familiarity with technologies. The set of technologies are: use of mobile phone; use of text messaging; use of palm computer; playing electronic games; usage of the Internet for finding maps or travel instructions; and having experience of VR. The purpose is to see if individuals are generally familiar with or have experience of these technologies. From the responses, all participants were familiar with the Internet and have had experience of using the Internet to find maps and travel instructions. They all also had knowledge of using mobile phones, although some of them expressed that they did not like using mobile phones due to personal preferences. Half of the participants used palm computers at least rarely, but all had experience of using computers. The majority of participants did not play electronic games (only three out of the twenty-seven participants played electronic games regularly). The participants had different levels of experiences of VR environments, such as on screen, projected wide screen and immersive VR. To conclude, although there are different levels of usage of these various technologies, all participants are technology-aware and familiar with using the Internet and computers. Therefore, the variables on differences in familiarity with technologies have not been considered further in this research.

The variable, VT(i) where i = 1 to 27, is the total score of the responses to the visio-spatial ability test in the pre-experiment questionnaire (see §6.1 and Appendix II). The results, summarised in Figure 8.3, show a range of scores with only one third of participants giving a correct answer to all five questions. These results will be further used in §8.2.3 in relation to other spatial variables.

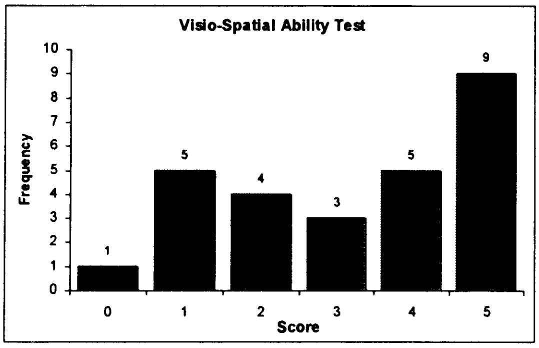


Figure 8.3 Results of visio-spatial ability test

8.2.2 Classifications

All 27 participants were grouped according to their self-assessed spatial ability which is represented through the four composite variables $\{S_{sd}(i), S_{mu}(i), S_{gsa}(i), S_{sa}(i)\}$ (where i = 1 to 27) discussed in the previous Section. Ward's method (Ward, 1963) with Euclidean distance was used to classify the participants. Ward's method is an analysis of variance approach and is generally regarded as effective though with some tendency to create small sized clusters. The data used are shown in Table 8.2 above. From the results shown in Figure 8.4, there is considerable linkage distance between three broad groups marked 1, 2 and 3. Because these three groups are established based upon the spatial ability variables SA$\{S_{sd}, S_{mu}, S_{gsa}, S_{sa}\}$, they are denoted as SA-G1, SA-G2 and SA-G3 in this thesis. A Kruskal-Wallis test was carried out for these three groups for each of the spatial ability variables. The Kruskall-Wallis test is a non-parametric equivalent of one-way ANOVA used to compare three or more groups based on ranks (Griffith and Amrhein, 1991). From the results shown in Table 8.3, the three groups are significantly different ($p < .005$) for all four variables $\{S_{sd}, S_{mu}, S_{gsa}, S_{sa}\}$ with respect to spatial ability. The three group classification is therefore taken as being sound.

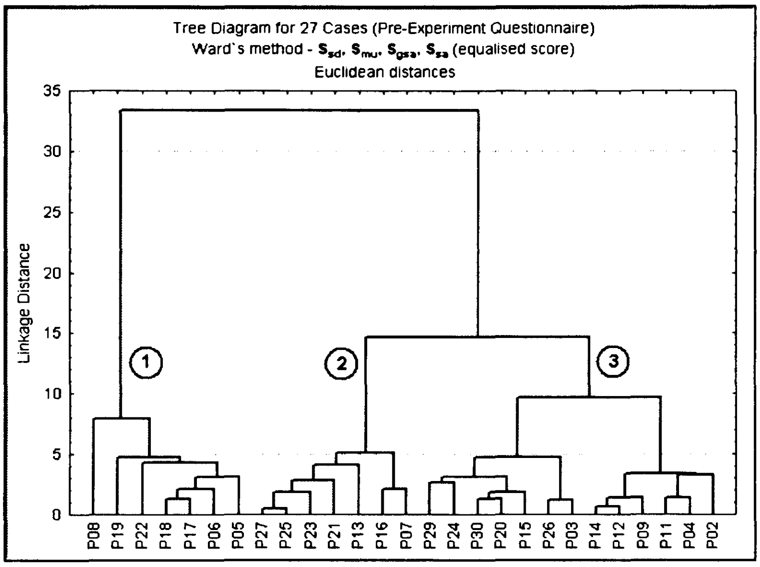
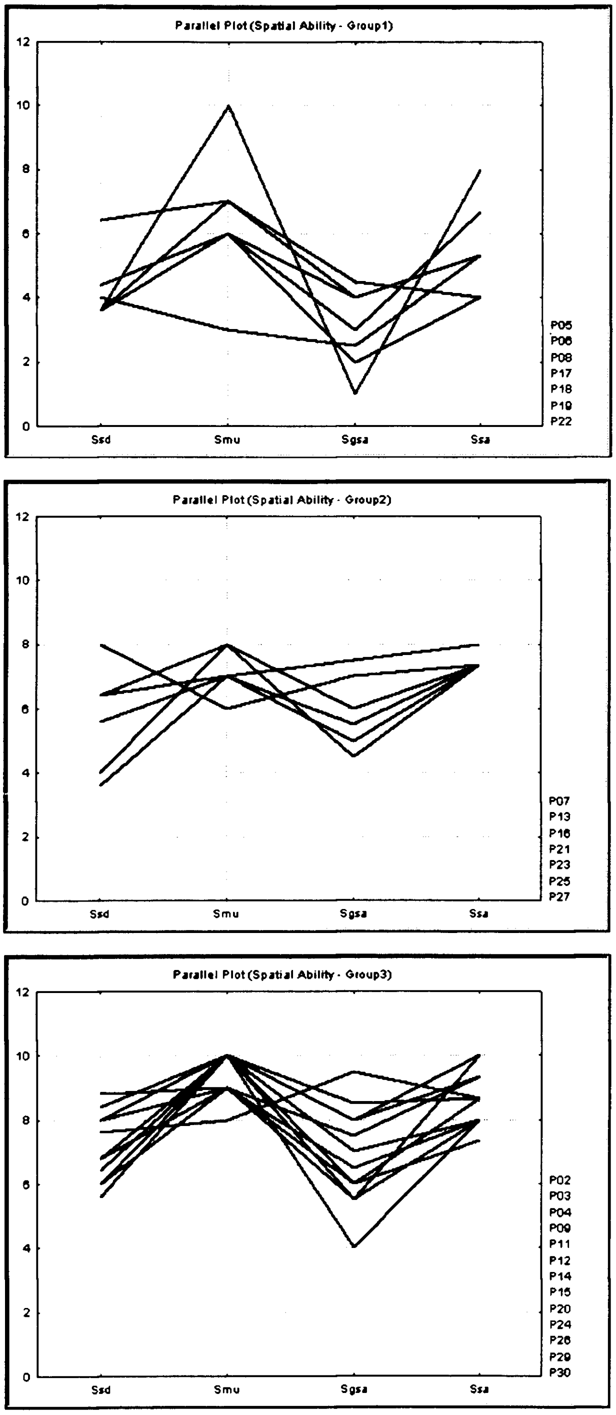


Figure 8.4 Classification based on participant spatial ability

Variable	Kruskal-Wallis test for three SA groups
S_{sd}	H (2, N= 27) =13.42423 p =.0012
S_{mu}	H (2, N= 27) =16.51543 p =.0003
S_{gsa}	H (2, N= 27) =14.89946 p =.0006
S_{sa}	H (2, N= 27) =17.49137 p =.0002

Table 8.3 Kruskal-Wallis test for three SA groups

The scores of all participants in the three different groups (SA-G1, SA-G2 and SA-G3) are plotted against the four spatial ability variables S_{sd}, S_{mu}, S_{gsa} and S_{sa} in parallel plots (Figure 8.5). The participants in Group SA-G1, shown in the parallel plot of Figure 8.5(a), generally have lower scores on all four variables compared with the other two groups, particularly on sense of direction S_{sd} and general spatial ability S_{gsa}. Compared with Group SA-G1 and Group SA-G2, the participants in Group SA-G3 have higher scores on all four variables as shown in Figure 8.5 (c). For the participants in Group SA-G2, the scores are generally intermediate between Group SA-G1 and Group SA-G2 (Figure 8.5(b)). These parallel plots also demonstrate that participants in all three groups assessed themselves with higher scores on map usage S_{mu}, and spatial awareness S_{sa} than the other two variables, that is sense of direction S_{sd} and general spatial ability S_{gsa}.



(a)

(b)

(c)

Figure 8.5 Parallel plots: individual scores for four variables S_{sd}, S_{mu}, S_{gsa}, S_{sa}:
(a) SA-G1; (b) SA-G2; (c) SA-G3

The classification using Ward's method was also carried out for 27 cases based on the variables $\{TK_{route}, TK_{landmark}, TK_{map}\}$, which indicate individual tendencies for route-oriented, landmark- oriented or map- oriented thinking. Three broad groups marked A, B and C in Figure 8.6 can be identified, and are denoted as TK-G1, TK-G2 and TK-G3 in this thesis. The Kruskal-Wallis test was also carried out for these three groups. The results, given in Table 8.4, show significant differences between the three groups ($p < .05$) for all three variables $\{TK_{route}, TK_{landmark}, TK_{map}\}$.

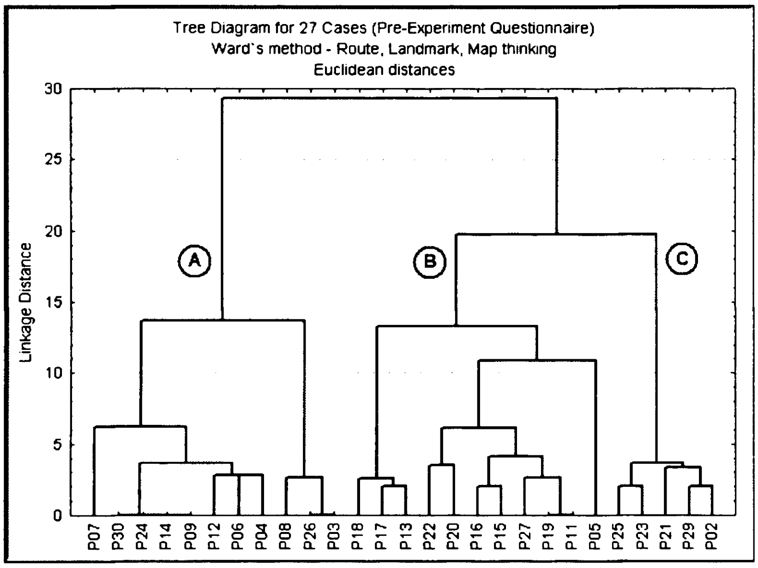


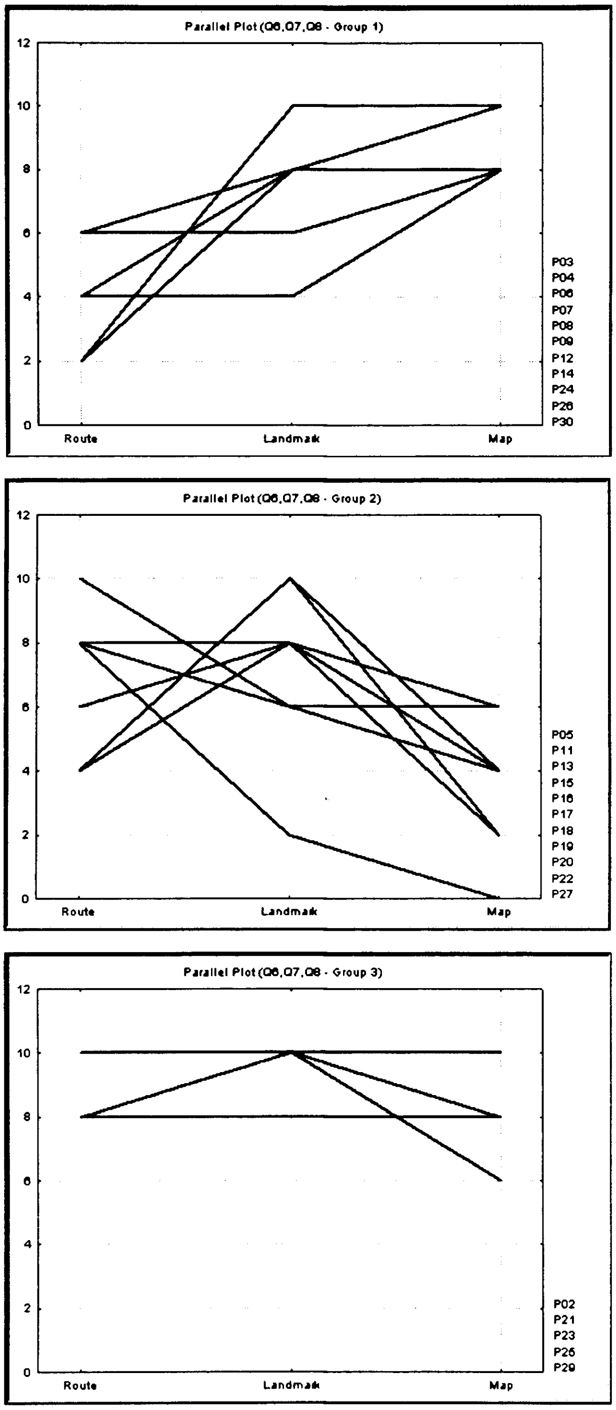
Figure 8.6 Classification of participant tendency for route, landmark and map thinking

Variable	Kruskal-Wallis test for three TK groups
Route	H (2, N= 27) =13.24033 p =.0013
Landmark	H (2, N= 27) =7.310186 p =.0259
Map	H (2, N= 27) =19.69620 p =.0001

Table 8.4 Kruskal-Wallis test for three TK groups

Parallel plots were also used to show the scores of the three variables TK_{route}, $TK_{landmark}$, TK_{map} for all participants in these three different groups (TK-G1, TK-G2 and TK-G3). The parallel plots for each group are given in Figure 8.7. Shown in Figure 8.7(a), Group TK-G1 exhibits a lower self-assessed tendency for route-orientated thinking with higher self-assessed tendency for map-orientated thinking alongside landmark-orientated thinking. Figure 8.7(b) indicates that Group TK-G2 has a self-assessed tendency for route-oriented thinking alongside landmark-orientated thinking with least self-assessed tendency for map-orientated thinking.

Group TK-G3 (Figure 8.7(c)) expressed a high self-assessed tendency for all modes of thinking. Moreover, as demonstrated in these parallel plots, the modes of thinking are not mutually exclusive amongst the participants with landmark-orientated thinking common to all three groups.



(a)

(b)

(c)

Figure 8.7 Parallel plots: individual scores for TK_{route}, $TK_{landmark}$, TK_{map}:
(a) TK-G1; (b) TK-G2; (c) TK-G3

Furthermore, the SA and TK groups were tested for differences in respect to variable VT – derived from the responses to the visio-spatial psychometric test. In both cases no significant differences were found. This would appear to be consistent with the opinion of some researchers (see §3.2.2) that psychometric testing has weak association with spatial ability in real-world wayfinding.

Discussion: As discussed in §3.2.2 and §3.4, individual spatial ability can be viewed from different perspectives and measured in different ways. Individual spatial ability has previously been studied in relation to various measures of wayfinding ability. In such studies, individuals have usually been grouped into having 'good' or 'poor' sense of direction according to their self-assessed spatial abilities (e.g. Cornell *et al.*, 2003). From the results presented here, three, rather than two, groups are identified based on composite variables S_{sd}, S_{mu}, S_{gsa} and S_{sa} with regard to individual sense of direction, map use, general spatial ability related to wayfinding and spatial awareness. The tests show that there are significant differences between each of these three groups. Two of these groups can be identified as self-perceiving 'good' (high SA-G3 scores) and 'poor' (low SA-G1 scores) spatial abilities. However, the existence of a third Group SA-G2 with intermediate but distinctive spatial ability scores suggests that self perception of individual spatial ability may not be as clear cut as the binary divide of 'good' versus 'poor' ability has previously suggested. This in turn suggests that the emphasis on studying individual spatial ability should be more on how such ability reflects on wayfinding behaviour. Moreover, the differences in individual spatial ability may also reflect differences in preference for different types of spatial information required while carrying out spatial tasks such as wayfinding.

Three different groups TK-G1, TK-G2 and TK-G3 were also identified regarding individual perceived tendencies towards route-oriented, landmark-oriented and map-oriented thinking for wayfinding activities. There is significant difference between these three groups according to the statistical test results (Table 8.4). These three tendencies correspond to the types of spatial knowledge discussed in §3.3.1. From the results shown in Figure 8.6 and Figure 8.7, the participants in Group TK-G1 perceive clear tendency towards map-oriented thinking, whilst the participants in Group TK-G2 perceive clear tendency towards route-oriented thinking. However, the results also indicate that the three groups are not identified with a single, mutually exclusive tendency for route-oriented, landmark-oriented or map-oriented thinking. In particular, landmark-oriented thinking is not a factor which could be used to differentiate between these groups. Participants in all three groups reported that they tend to have landmark-oriented thinking. Thus, landmarks could be considered as an important element in both route-oriented and map-oriented thinking.

Regarding the three variables TK_{route}, $TK_{landmark}$, TK_{map}, the Kruskal-Wallis test indicates that there is no significant difference between three spatial ability groups SA-G1, SA-G2 and SA-G3. A cross classification table (Table 8.5) is used here to show the number of participants in each of three SA groups (SA-G1, SA-G2 and SA-G3) and in three TK groups (TK-G1, TK-G2 and TK-G3). Interestingly, the numbers in Table 8.5 display that the majority of the participants in Group SA-G3 (with high score in spatial ability) tend towards map-oriented thinking, whilst a larger proportion of the participants in Group SA-G1 (with low score in spatial ability) tend towards route-oriented thinking. The participants in Group SA-G2 (with intermediate score in spatial ability) tend to have mixed modes of thinking. In other words, there is no clear majority of participants in Group SA-G2 who tend to prefer one of route-oriented, landmark-oriented or map-oriented thinking.

	TK-Group		
SA-Group	TK-G1 (map + landmk)	TK-G2 (route + landmk)	TK-G3 (all)
SA-G1 (low score)	2	5	
SA-G2 (intermediate score)	1	3	3
SA-G3 (high score)	8	3	2

Table 8.5 A cross classification of SA groups and TK groups

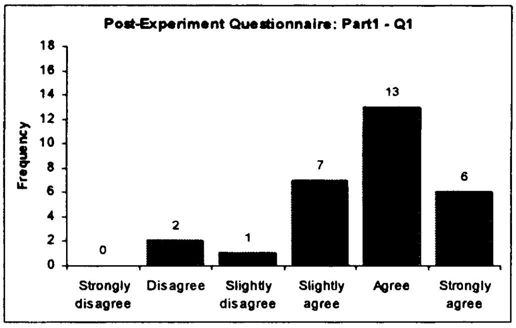
These spatial ability groups and their self-perceived tendencies towards route/landmark/map thinking groups will be analysed together with their observed spatial information usage and observed wayfinding behaviours in later sections.

8.3 Analysis of Post-Experiment Questionnaire

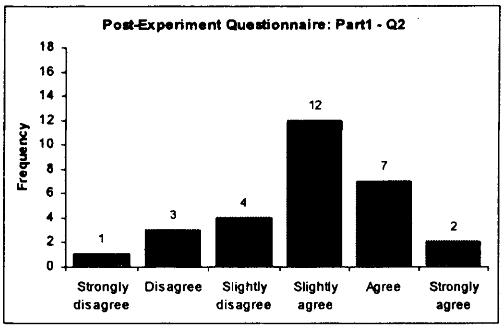
Part of the post-experiment questionnaire has important bearing on the validity of the experiment in VR environment. Thus this Section examines participant feedback on sense of presence in the VR test environment and the commonality of wayfinding strategies used in VR test environment and in the real-world prior to analysis of wayfinding data. In part I of the post-experiment questionnaire, questions Q1 to Q6 elicited the feedback information stated on the captions to Figures 8.8 (a) to (f). The focus of the responses shown in Figure 8.8 (a) to (d) is on the sense of presence after the wayfinding experiences in the VR test environment. There were 29[1] participants who answered this part of the questionnaire. From all four questions, the balance is clearly that most respondents experienced a sense of presence, which is consistent with the studies discussed in §4.2. Figure 8.8(e) shows that a smaller majority (19 of 27) of participants agree that they remember their experience of the

[1] 27 participants complete all parts of total experiments. Two participants only complete most of one set of wayfinding and Part I of feedback questionnaire (§7.4). Hence 29 participant responses are analysis in this Section.

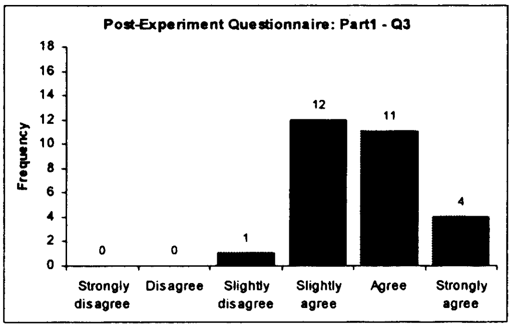
virtual town in the same way as they would remember places they had visited. The responses to the further two questions which emphasise the feedback on their wayfinding behaviour in VR environments reveals the overwhelming view that participants felt that they used a similar approach and similar features in the VR environment for wayfinding as in the real world.



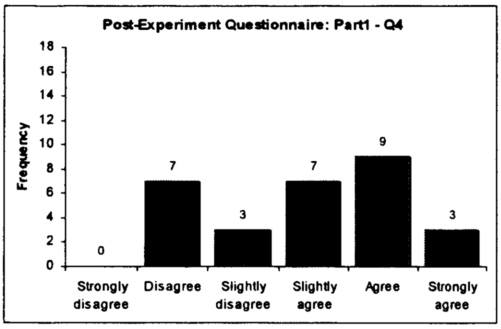
(a) have a sense of 'being there' in the street



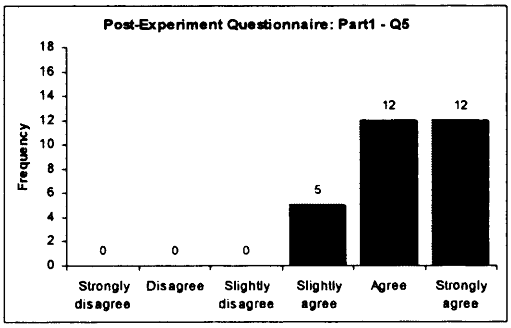
(b) the virtual town becomes the 'reality', almost forget about the 'real world' of the laboratory



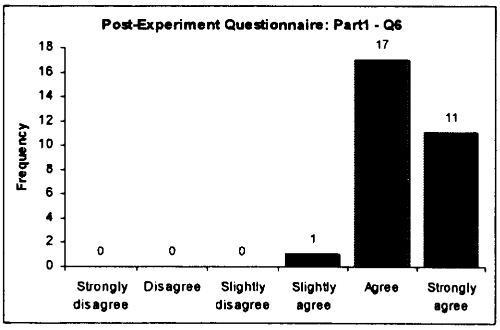
(c) feel like just visited somewhere instead of just looking at some images



(e) remember the virtual town experienced in the same way as remembering some visited places



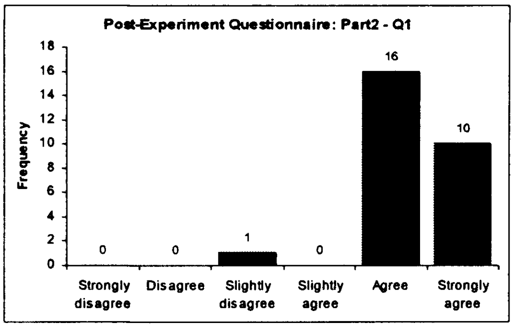
(e) find my way in these VR environments in a similar approach as I do in the real world



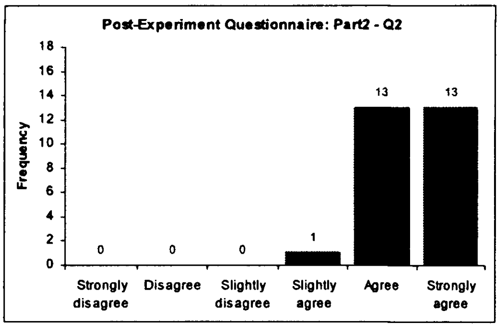
(f) use similar features to find my way around in these VR environments as I do in the real world

Figure 8.8 Bar charts of responses of the post experiment questionnaire Part I (Q1 to Q6)

In part 2 of the questionnaire, which was completed by participants after their wayfinding tasks in the second setting, two of the questions shown in Figure 8.8(e) and (f) in the part I were repeated so that consistency of the responses could be seen. There are 27 participants who answered these two questions in part 2 because two of 29 participants only completed the wayfinding tasks in one of the settings. Shown in Figure 8.9 (b), all 27 participants agreed that they use similar features in the VR environment for wayfinding as in the real world, whilst 26 out of 27 participants agreed that they use a similar approach in the VR environment for wayfinding as in the real world. Moreover, the responses from the debrief interview further confirmed the commonality in the strategies and features used in wayfinding during the experiment and that used in the real world.



(a) find my way in these VR environments in a similar approach as I do in the real world



(b) use similar features to find my way around in these VR environments as I do in the real world

Figure 8.9 Bar charts of responses of the post experiment questionnaire Part 2 (Q1 and Q2)

Discussion: The responses elicited from the above questions show the general agreement among the participants that there is a degree of sense of presence whilst they were in the VR urban environments. As discussed in Chapter 4, because of the ethereal nature of 'presence' and the ways in which participants might interpret and measure the degree of 'being' there, it was anticipated that the responses to these questions would show various levels of certainty. The results shown here are consistent with the general findings in the studies discussed in §4.2 and §4.3. More importantly, the responses to the two questions which concern the commonality of wayfinding strategies used in the VR test environment and in the real-world shows that all participants reported that they use a similar approach and features in the VR urban environments during the wayfinding experiments as they do in the real world. This finding is consistent between the two sets of wayfinding experiments. This has important bearing on the validity of the methodology adopted in these experiments.

8.4 Position, Distance and Time

In this Section the focus is on the $P_i(t, X, Y)$ i = 1 to 27 collected every second on participants' movements while undertaking the wayfinding tasks in the two urban settings. The track position can be studied as intensity maps whilst the two key variables extracted from the tracks – distance travelled and time taken for completion – can also be analysed. The positional track data, as discussed in §8.1.1, were transformed into the GB National Grid coordinate system. Thus, all position points could be referenced with the corresponding features in the OS MasterMap™ product. Furthermore, from the positional data, the distance travelled for each wayfinding task can be calculated for all participants. Also, for each participant, the completion time can be calculated for each wayfinding task. There are six separate wayfinding tasks to different destinations as from a starting point to D1, D1 to D2, D2 to D3, D3 to D4, D4 to D5 and returning to the starting point (see §6.4). These 6 tasks will be referred to as Route1 to Route6 in this thesis.

8.4.1 Spatial Distribution of Tracks

From the complete positional track data for each of the 27 participants, a general picture can be mapped of the routes that are most frequently travelled and the locations where participants tend to pause or stop. For urban setting U1, the 27 positional data tables were combined to form a new positional data table comprising all participant track data. This combined file contained a total 43,985 points. An intensity map (Figure 8.10) of these track points was created in ArcGIS, using kernel density estimation with a 1 metre grid cell and a 10 metre bandwidth. The intensity map was overlain onto the base map of the area, marked with starting/finishing points of the prescribed wayfinding tasks and the five destinations for each of the tasks (D1 to D5). As shown in Figure 8.10, the locations with highest densities are the start point of the whole wayfinding experiment and the destinations of each separate task (which are also the start points for the next task in the sequence) where the participants usually access information from the PDA as part of their planning/determining which routes are to be taken next. Another set of locations with high intensity are road junctions; however, some of the road junctions have higher intensities than others. Some road junctions present only a simple choice of routes that might be taken, whilst others pose greater challenges, as manifest by the higher intensities at roundabout junctions compared with other junctions in this setting. In addition, the diversity of routes taken by participants to reach the same destinations can also be clearly seen, although some routes are shown as having been taken more frequently as options than others. The intensity map also illustrates that some starting points for individual tasks have higher densities than others. For instance, the density for the starting points at D1 and D2 are higher than at D4. Hence less time is spent on average at D4 than at D1 and D2 before taking the route for the next task.

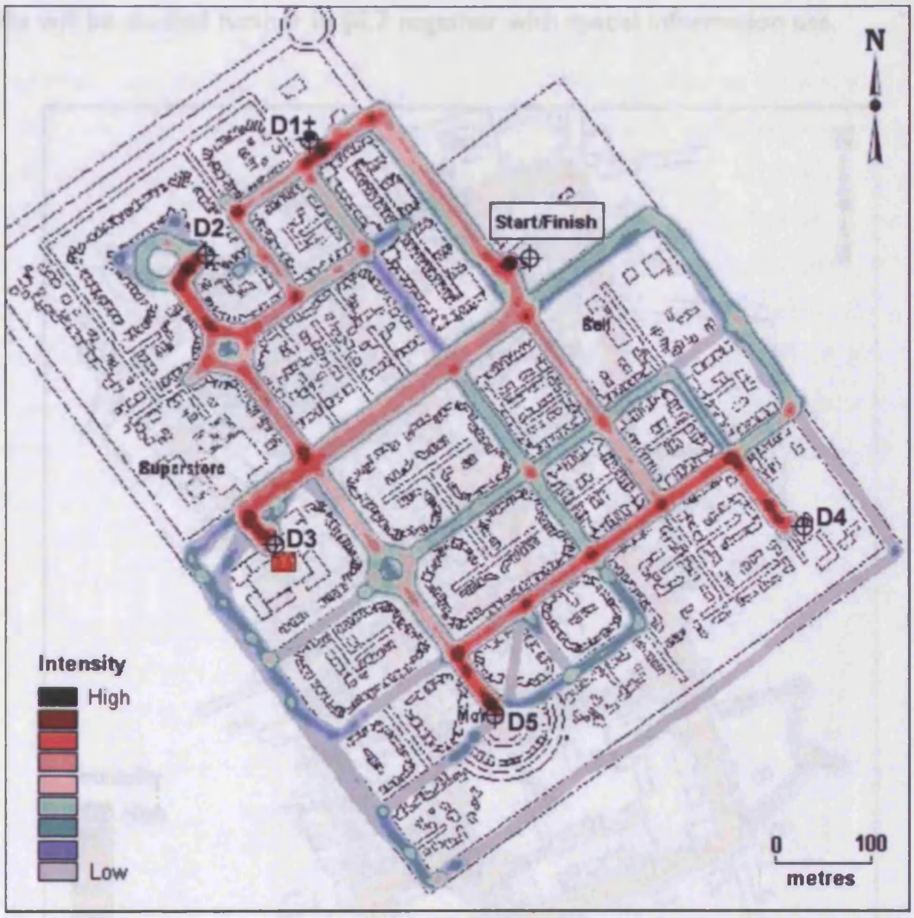


Figure 8.10 Intensity map of track points for all participants – setting U1

The same procedure was carried out to create an intensity map for all positional track points (all 27 participant tracks) in urban setting U2. There are a total of 44,156 track points. This intensity map was also overlain onto the base map for the area, with starting/finishing points and the five destinations for each task (D1 to D5) marked (Figure 8.11). Destinations D1 to D5 also served as the starting point for the subsequent wayfinding task. From this density map, a similar pattern can be identified as in setting U1 (Figure 8.10), that is, the highest densities are mostly located at starting points. At some of the destination points such as D2 and D3, there are several high intensity points rather than a single high density point. This is because these locations are more open (wider space), as in the case of squares which have a number of arrival points and many choices for leaving on the next task. Another set of locations with high intensities are road junctions. These appear different from the density distributions at road junctions in setting U1, as most of the road junctions in setting U2 consistently have higher intensities. This suggests that most of the junctions in U2 pose greater wayfinding challenges than those in U1. Diversity of routes taken can also be observed. Another particular location in this setting is a cul-de-sac with very high densities. Here the spatial layout posed certain difficulties for certain participants in their wayfinding tasks. This will be studied further in §8.7 together with spatial information use.

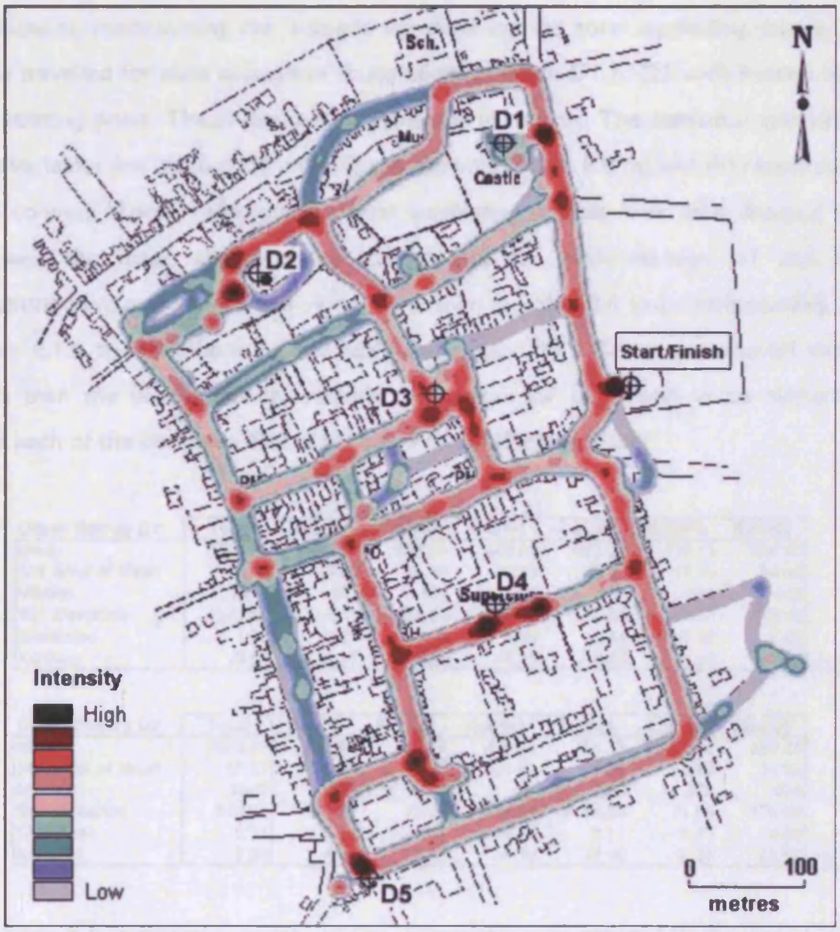


Figure 8.11 Intensity map of track points for all participants – setting U2

From the data recorded, all 27 participants reached the prescribed destinations in both settings. Hence, all participants were able to find their way using the information accessed through the PDA, although some experienced greater difficulty than others. As shown in Figure 8.10 and Figure 8.11, different routes were chosen by participants. The completion times also varied amongst the participants for each of the wayfinding tasks. The following sections will discuss the distance travelled variable and the completion time variable derived from the positional data. In the Sections that follow, a 'route' denotes the path taken between successive destinations and the routes are numbered thus: Route1 for the path taken to destination D1.

8.4.2 Distance Travelled

Distances travelled during the wayfinding tasks, denoted as $D_{travelled}$, were calculated for each setting from the positional track data $P_i(t_i, X_i, Y_i)$, i = 1 to 27 (for each of the 27 participants). Six variables were derived: $D_{travelled\text{-}total}$, $D_{travelled\text{-}R1}$, $D_{travelled\text{-}R2}$, $D_{travelled\text{-}R3}$, $D_{travelled\text{-}R4}$, $D_{travelled\text{-}R5}$ and $D_{travelled\text{-}R6}$, representing the distance travelled for the total wayfinding journey and the distance travelled for each successive route taken to reach D1 to D5 with Route6 the return to the starting point. These $D_{travelled}$ variables are in metres. The statistical summary of the $D_{travelled}$ variables for settings U1 and U2 are shown in Table 8.6 (a) and (b) respectively. The second column, 'Total', refers to the total wayfinding journey. For total distance travelled, $D_{travelled\text{-}total}$, the mean approximates the median for both settings U1 and U2. The distributions have a slight positive skew. As shown in Table 8.6 and corresponding boxplots in Figure 8.12, the distribution of variable $D_{travelled\text{-}total}$ for U2 is more skewed with higher kurtosis than the distribution of variable $D_{travelled\text{-}total}$ for U1. There is an outlier/extreme value in each of the boxplots, P02 in U1 and P17 in U2 respectively.

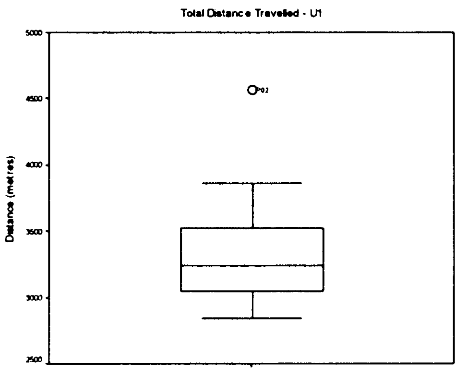
Urban Setting U1	Total	Route1	Route2	Route3	Route4	Route5	Route6
Mean	3313.44	317.13	452.08	449.61	898.30	516.13	680.20
Std. Error of Mean	74.99	10.23	24.35	29.73	33.38	11.45	24.42
Median	3242	297	425	398	837	509	640
Std. Deviation	389.65	53.15	126.53	154.50	173.45	59.52	126.90
Skewness	1.38	2.07	2.32	3.66	2.44	1.48	1.89
Kurtosis	2.64	3.97	9.55	15.78	6.04	4.10	2.19

(a)

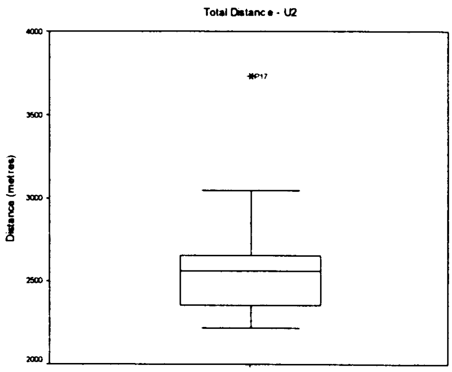
Urban Setting U2	Total	Route1	Route2	Route3	Route4	Route5	Route6
Mean	2570.27	236.94	420.16	402.83	454.13	402.97	653.26
Std. Error of Mean	60.37	6.08	13.90	25.82	18.33	13.82	34.00
Median	2563	229	400	397	420	370	604
Std. Deviation	313.71	31.61	72.25	134.15	95.23	71.83	176.68
Skewness	2.11	2.01	1.68	0.75	0.71	0.79	4.63
Kurtosis	6.30	4.94	3.18	-0.30	-0.48	-0.36	22.57

(b)

Table 8.6 Statistical summary of $D_{travelled}$ variables: (a) setting U1; (b) setting U2.



(a)



(b)

Figure 8.12 Boxplots for $D_{travelled\text{-}total}$ (n=27): (a) setting U1 and (b) setting U2.

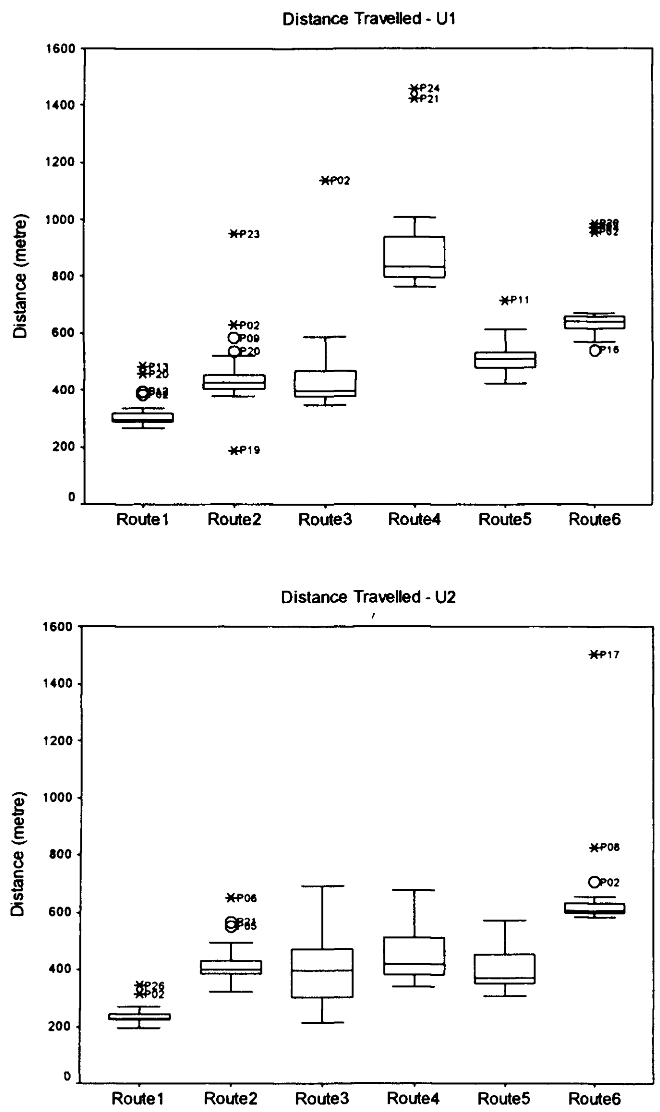
In order to test the normality of the distribution $D_{travelled\text{-}total}$, the Shapiro-Wilk test was chosen because the size of sample in these two data sets are both < 50. From the results shown in Table 8.7, the null hypothesis (H_0) can be rejected for $D_{travelled\text{-}total}$ in both U1 and U2. However, when the respective outlier/extreme values (P02 for U1, P17 for U2) are removed then H_0 can be accepted and the data taken as normally distributed. Thus the non-normality of the distributions is derived from a single outlier/extreme value in each case. It is worth noting that the participants that are outlier/extreme value are different in each case (P02 in setting U1, P17 in setting U2) and that it is not one participant who travelled further and took more time such as might occur with someone seriously getting lost in both settings. Nevertheless it would be prudent to use non-parametric test for statistical inference.

Urban Setting U1	Statistic	df	Sig.	***Urban Setting U2***	Statistic	df	Sig.
Dtravelled-total	0.892	27	0.01**	Dtravelled-total	0.816	27	0.01**
Dtravelled-total less P02	0.934	26	0.112	Dtravelled-total less P17	0.937	26	0.152

** This is an upper bound of the true significance.

Table 8.7 Normality test for variable $D_{travelled\text{-}total}$ (n=27)

Statistical summaries for the distance variable for individual routes are also given in Figure 8.6 (a) and (b). There is a considerable variability in the distributions in each of the routes in both settings. The variable distributions for some of the routes are more skewed and with higher kurtosis than others. This is also illustrated in the boxplots in Figure 8.13 (a) and (b). The median values are a good reflection of the relative length of route choices between successive destinations. The range of values in each boxplot arises from the individual route choices, some being longer than others. There are considerable numbers of outlier/extreme values. P02 in setting U1 generates outliers and extreme values in four out of the six routes, reflecting that this participant often became confused and repeated sections of route. P17 in U2 as an extreme value in $D_{travelled\text{-}total}$ discussed above (Figure 8.12 (b)), however, is an extreme value only in Route6. In this setting, P02 also appears as an outlier/extreme value in two of the routes for the same reasons as in U1. From the boxplots, it can be observed that, other than in the case of P02, it is not the same individuals that always generate outlying and extreme values. Thus, the differences in the distribution of each $D_{travelled}$ variable appear to vary according to the perceived complexity (by the participants) of route choice between successive destinations.



(a)

(b)

Figure 8.13 Distance travelled for six separated wayfinding tasks: (a) setting U1 (n=27); (b) setting U2 (n=27)

As discussed in §6.4 and Table 7.1, half of the participants started the first set of wayfinding tasks in setting U1, whilst the other half started in setting U2, in order to control in the experimental design for the effects of sequencing. The variable $D_{travelled\text{-}total}$ between these two groups of participants is now tested to see if there is any sequence effect. 14 participants took U1 as their first setting for the wayfinding experiment, and another 13 participants took U1 as their second setting. A Mann-Whitney U test was used: $U(14, 13) = 87.00$, $p = 0.867$. The H_0 hypothesis could not be rejected. Therefore, this result shows that there is no significant difference in this variable between the participants starting U1 as their first setting and the participants taking U1 as their second setting. The same test was carried out for setting U2 with following result: $U(13, 14) = 75.00$, $p = 0.458$. Again, the H_0 hypothesis cannot be rejected. Thus, for both settings, the sequence in which the settings were used had no significant influence on the distance travelled or the routes chosen by the participants.

8.4.3 Completion Time

From the positional track data $P_i(t_i, X_i, Y_i)$ i = 1 to 27, the time taken to complete wayfinding tasks for each route and the total journey in each setting was calculated based on t_i and the (X, Y) locations of starting and finishing points of each task. This variable, denoted as $T_{completion}$ in this thesis, is the completion time. There is a set of $T_{completion}$ variables: $T_{completion\text{-}total}$, $T_{completion\text{-}R1}$, $T_{completion\text{-}R2}$, $T_{completion\text{-}R3}$, $T_{completion\text{-}R4}$, $T_{completion\text{-}R5}$ and $T_{completion\text{-}R6}$ representing the completion time for the total journey, Route1, Route2, Route3, Route4, Route5 and Route6 respectively. These variables are in seconds. The variable $T_{completion}$ was calculated for all 27 participants for both settings U1 and U2. The statistical summary of the $T_{completion}$ variables is shown in Table 8.8 (a) and (b). The second column, 'Total', refers to the total wayfinding journey. The mean of total completion time, $T_{completion\text{-}total}$, approximates the median for both setting U1 and U2. The distribution of $T_{completion\text{-}total}$ for setting U1 has a slight positive skew, with less for setting U2. Boxplots for $T_{completion\text{-}total}$ in each setting are given in Figure 8.14 (a) and (b). There is an outlier value (P23) in setting U1 and an outlier value (P05) in setting U2.

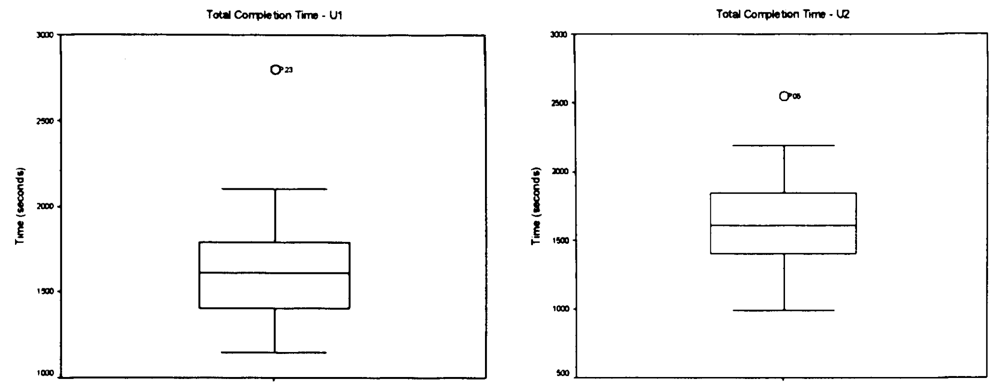
Urban Setting U1	Total	Route1	Route2	Route3	Route4	Route5	Route6
Mean	1629.07	176.81	275.63	241.04	405.67	243.93	286.00
Std. Error of Mean	67.26	10.67	28.06	21.18	19.55	12.55	10.75
Median	1610	165	257	209	399	222	271
Std. Deviation	349.48	55.46	145.78	110.07	101.58	65.19	55.87
Skewness	1.46	1.06	3.44	2.06	0.85	0.52	0.59
Kurtosis	3.62	0.87	14.95	4.41	0.32	-0.79	-0.79

(a)

Urban Setting U2	Total	Route1	Route2	Route3	Route4	Route5	Route6
Mean	1630.56	166.48	243.44	257.81	324.89	333.70	304.22
Std. Error of Mean	64.94	12.79	14.47	21.45	23.80	16.65	18.98
Median	1605	157	240	219	292	301	278
Std. Deviation	337.42	66.48	75.17	111.48	123.68	86.50	98.64
Skewness	0.55	1.16	0.74	1.31	0.45	0.68	1.21
Kurtosis	1.01	0.92	-0.07	1.64	-0.47	-0.12	0.78

(b)

Table 8.8 Statistical summary of $T_{completion}$ variables: (a) setting U1; (b) setting U2.



(a) (b)

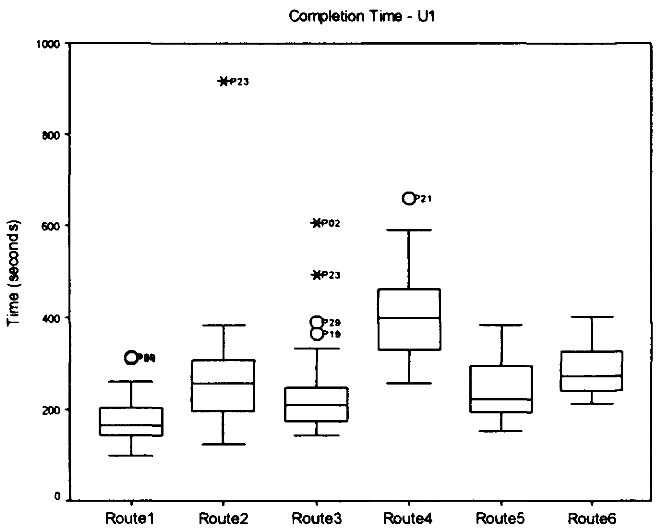
Figure 8.14 Boxplots of $T_{completion\text{-}total}$ (n=27): (a) setting U1; (b) setting U2.

As with $D_{travelled\text{-}total}$, a test for normality was carried out on the variable $T_{completion\text{-}total}$ for settings U1 and U2. Table 8.9 gives the results of a Shapiro-Wilk test. For setting U1, the null hypothesis (H_0) of no difference can be rejected at $p < .05$; however, when the outlier value (P23) is removed then H_0 cannot be safely rejected and the data can be accepted as normally distributed. For setting U2, the H_0 cannot be rejected safely and the data can be accepted as normally distributed.

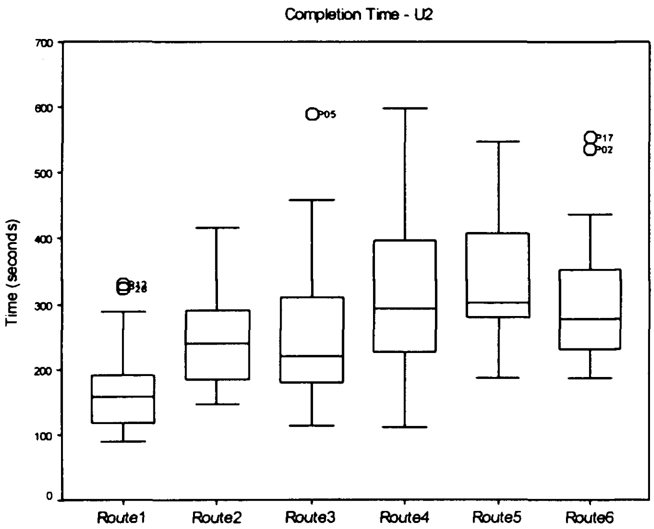
Urban Setting U1	Statistic	df	Sig.	***Urban Setting U2***	Statistic	df	Sig.
Tcompletion-total	0.9	27	0.015	Tcompletion-total	0.973	27	0.681
Tcompletion-total less P23	0.967	26	0.545				

Table 8.9 Normality test for the total completion time

The completion time for each route in both setting U1 and U2 were also calculated. From the statistical summary (Table 8.8 (a) and (b)) and the boxplots (Figure 8.15 (a) and (b)) for these variables ($T_{completion\text{-}R1}$, $T_{completion\text{-}R2}$, $T_{completion\text{-}R3}$, $T_{completion\text{-}R4}$, $T_{completion\text{-}R5}$ and $T_{completion\text{-}R6}$), considerable variation in the distributions can be observed. The distributions of the variables $T_{completion}$ are highly skewed for some of routes. The median values are a good reflection of the relative completion time for reaching successive destinations. The range of values for each boxplot reflects individual completion times, showing that some participants took longer than others. There are a good few numbers of outlier/extreme values on some of the routes, such as Route3 in setting U1. This illustrates that some participants took considerably longer to complete this wayfinding task than others. Some routes have a wider spread but no outliers, such as Route4 in setting U2. However, there is no single individual who consistently takes longer or shorter times to complete every one of the routes. Thus the variable $T_{completion}$ appears to be influenced by the participant difficulty in determining routes between successive destinations, and the time taken for accessing and assimilating information through the PDA.



(a)



(b)

Figure 8.15 Completion time for each route (n=27): (a) setting U1; (b) setting U2

In order to establish any significant difference arising from the sequence in which the settings were used, the variable $T_{completion\text{-}total}$ was also tested in the same way as discussed in §8.4.2 for the variable $D_{travelled\text{-}total}$. For setting U1, 14 participants were required to take U1 as their first setting in which to start their wayfinding tasks, and the other 13 participants took U1 as their second setting. The result of a Mann-Whitney U test is: $U(14, 13) = 46.00$, $p = 0.029$. Thus the H_0 of no significant difference can be rejected at $p < 0.05$ level, giving a significant difference in $T_{completion-total}$ between these two groups of participants. For setting U2, 13 participants took U2 as their first setting, and another 14 participants took U2 as their second setting. The result, U(13, 14) = 57.00, $p = 0.105$, shows that H_0 cannot be rejected. Thus, for setting U2 there is no significant difference in $T_{completion-total}$ between the two groups. However, with regard to the statistically significant result for U1 , only Route6 is significantly different at $p < 0.05$ (Table 8.10). For individual routes in setting U2, there is a significant difference at $p < 0.05$ in Route4 only. The result for $T_{completion-total}$ in setting U1 is clearly an effect of aggregation. Therefore, on the basis of this analysis of each of the two complete routes, it seems reasonable to conclude that the overall differences in the variable $T_{completion}$, particularly on individual tasks, do not show any consistently significant change resulting from their experience in their wayfinding in the first setting.

Urban Setting U1	**Route1**	**Route2**	**Route3**	**Route4**	**Route5**	**Route6**
Mann-Whitney U	69	51.5	52.5	85	56	49
Asymp. Sig. (2-tailed)	0.286	0.055	0.062	0.771	0.089	0.041
Exact Sig. [2*(1-tailed Sig.)]	0.302	0.054	0.061	0.793	0.094	0.043

Urban Setting U2	**Route1**	**Route2**	**Route3**	**Route4**	**Route5**	**Route6**
Mann-Whitney U	67	71	84	50.5	68.5	81
Asymp. Sig. (2-tailed)	0.244	0.332	0.734	0.049	0.275	0.627
Exact Sig. [2*(1-tailed Sig.)]	0.259	0.35	0.756	0.048	0.28	0.65

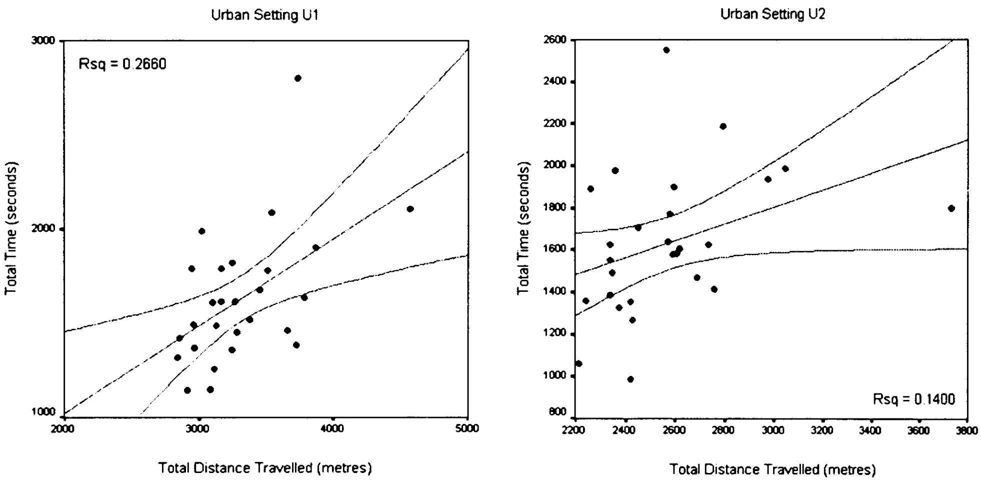
Table 8.10 Significance test for differences in sequence by route for settings U1 and U2.

8.4.4 Time and Distance

The completion time and the distance travelled are two obvious variables for assessing wayfinding task performance. The correlations between these two variables could vary according to the differences in routes travelled, the time spent for accessing information for assisting wayfinding, the stopping time for either observing or hesitating, and so on. Table 8.11 shows the correlation between $T_{completion-total}$ and $D_{travelled-total}$ for all wayfinding tasks (from a starting point and back to the starting point) in both setting U1 and U2. The correlations are: 0.518 (significant at $p < .05$ and also $p < .01$ for setting U1 and 0.465 significant at $p < .05$ level for setting U2). The scatter diagrams (Figure 8.16) also illustrate the relationship between the variables $T_{completion-total}$ and $D_{travelled-total}$. However, the low R^2 for both settings shows that total distanced travelled does not explain sufficient variance in the total time taken, perhaps counter to what one might expect. Thus from the scatter diagrams, it is easy to pick out participants who have travelled further than average and yet covered the distance relatively quickly and others who have travelled no further than average yet covered the distance relatively slowly. This relationship for setting U2 (Figure 8.16(b)) is still weaker than that for setting U1 (Figure8.16(b)).

Urban Setting U1			$T_{completion-total}$
Spearman's rho	$D_{travelled-total}$	Correlation Coefficient	0.518
		Sig. (2-tailed)	0.006
		N	27
Urban Setting U2			$T_{completion-total}$
Spearman's rho	$D_{travelled-total}$	Correlation Coefficient	0.465
		Sig. (2-tailed)	0.015
		N	27

Table 8.11 Correlation coefficients between distance travelled and completion time in settings U1 and U2.



(a) (b)

Figure 8.16 Regression of total completion time again total distance travelled with 95% confidence limits: (a) setting U1; (b) setting U2.

The relationship between $T_{completion}$ and $D_{travelled}$ was further studied for each of the six wayfinding tasks (Route1 to Route6). The scatter diagrams were plotted with same scale on x, y axis throughout for visual comparison (Figure 8.17 and Figure 8.18). Firstly, what can be observed is that the nature of the relationship between $T_{completion}$ and $D_{travelled}$ for each route varies. For setting U1 (Figure 8.17), some routes have a higher R^2 between variables $T_{completion}$ and $D_{travelled}$ than others. For example, the R^2 for Route3 (Figure 8.17(c)) is the highest (though influenced by the positive leverage effect of an outlier), and the lowest is R^2 shown for Route6 in Figure 8.17(f), in which most of participants have very similar values on the distanced travelled but considerable variation in time taken. This phenomenon can also be observed in setting U2 (Figure 8.18). For instance, for both Route1 and Route6, the distance travelled, $D_{travelled}$, varies little yet completion times $T_{completion}$ are highly variable (particular in Route6, ignoring the outlier). When considered in isolation, the variables $T_{completion}$ and $D_{travelled}$ for Route3 and Route4 have stronger correlations than the other routes. These results may be manifestations of the variable complexity in the layout of the chosen routes, the variable time necessary for information access, and variation in any time spent whilst lost or confused. Secondly, the relationship between the two variables $T_{completion}$ and $D_{travelled}$ in each route shows differences when comparing settings U1 with U2. For example, the relations shown in Route6 for both settings (Figure 8.17(f) and Figure 8.18(f)) indicate that there is greater diversity in completion time, $T_{completion}$, for the participants when in setting U2 than in U1. In addition, the outlier points, such as the ones shown in Figure 8.17 (b), (c), (d), (f) and Figure 8.18(f), could seriously affect the measures of central tendency. Therefore, the regression lines and their R^2 values are sometimes biased as a result, though the scatter diagrams can still allow the more detailed pattern to be visualised.

The correlation of $T_{completion\text{-}total}$ and $D_{travelled\text{-}total}$ for the aggregated routes in U1 and U2 does not appear to be a good reflection of the relationship for each route (the individual wayfinding tasks). From the relationship between the completion time and distance travelled, it appears that the perceived complexity and different spatial layout of each route affects participant ability in wayfinding. Furthermore, for the similar distance travelled, the variable $T_{completion}$ can differ between different routes and does not form the expected strong relationship of longer time for longer distance travelled. This may arise because a certain proportion of the time is being used to plan each route and otherwise accessing and assimilating information from the PDA. The time spent on accessing information via the PDA will be investigated in the next Section.

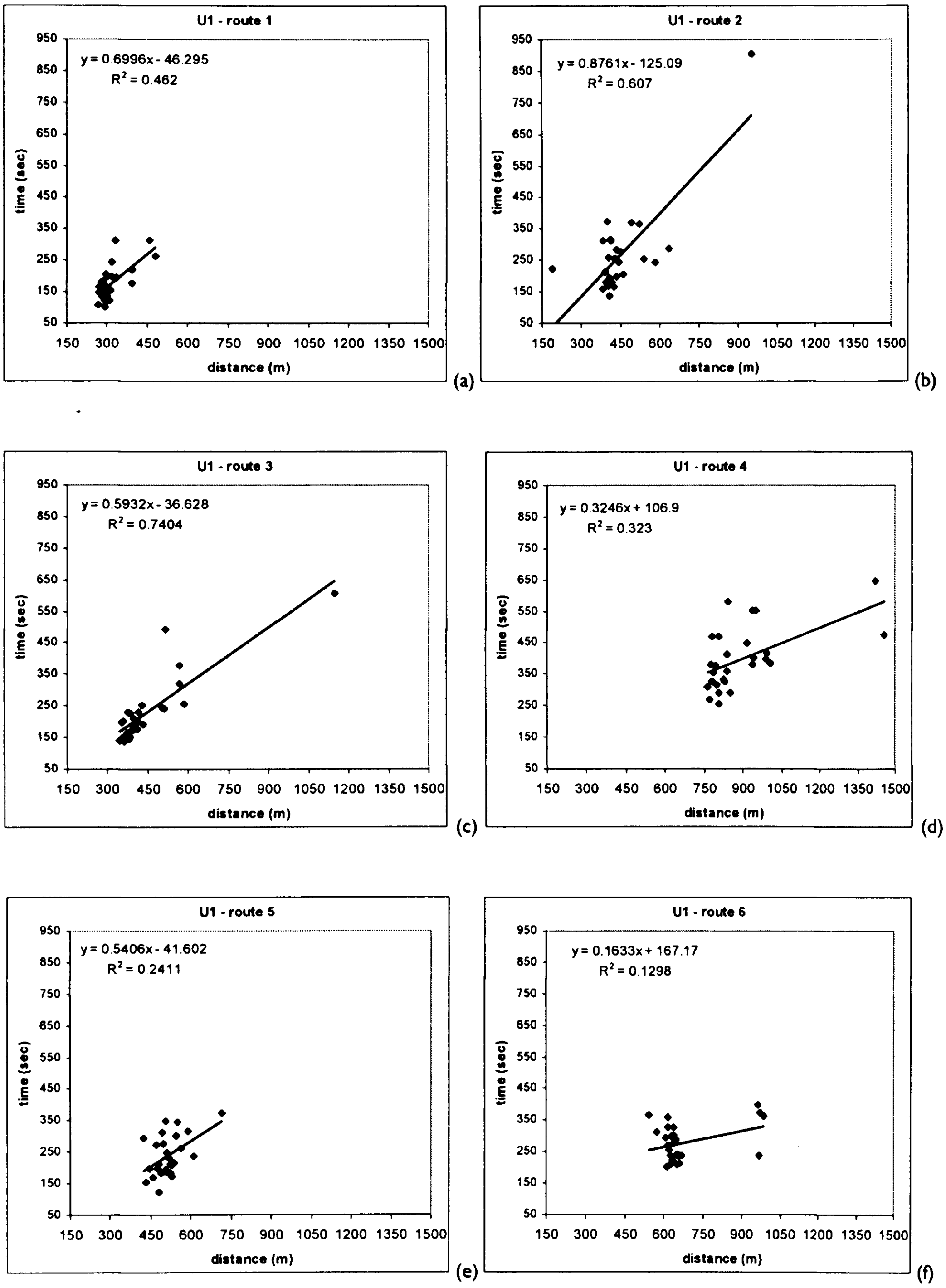


Figure 8.17 Time against distance for six routes in setting U1.

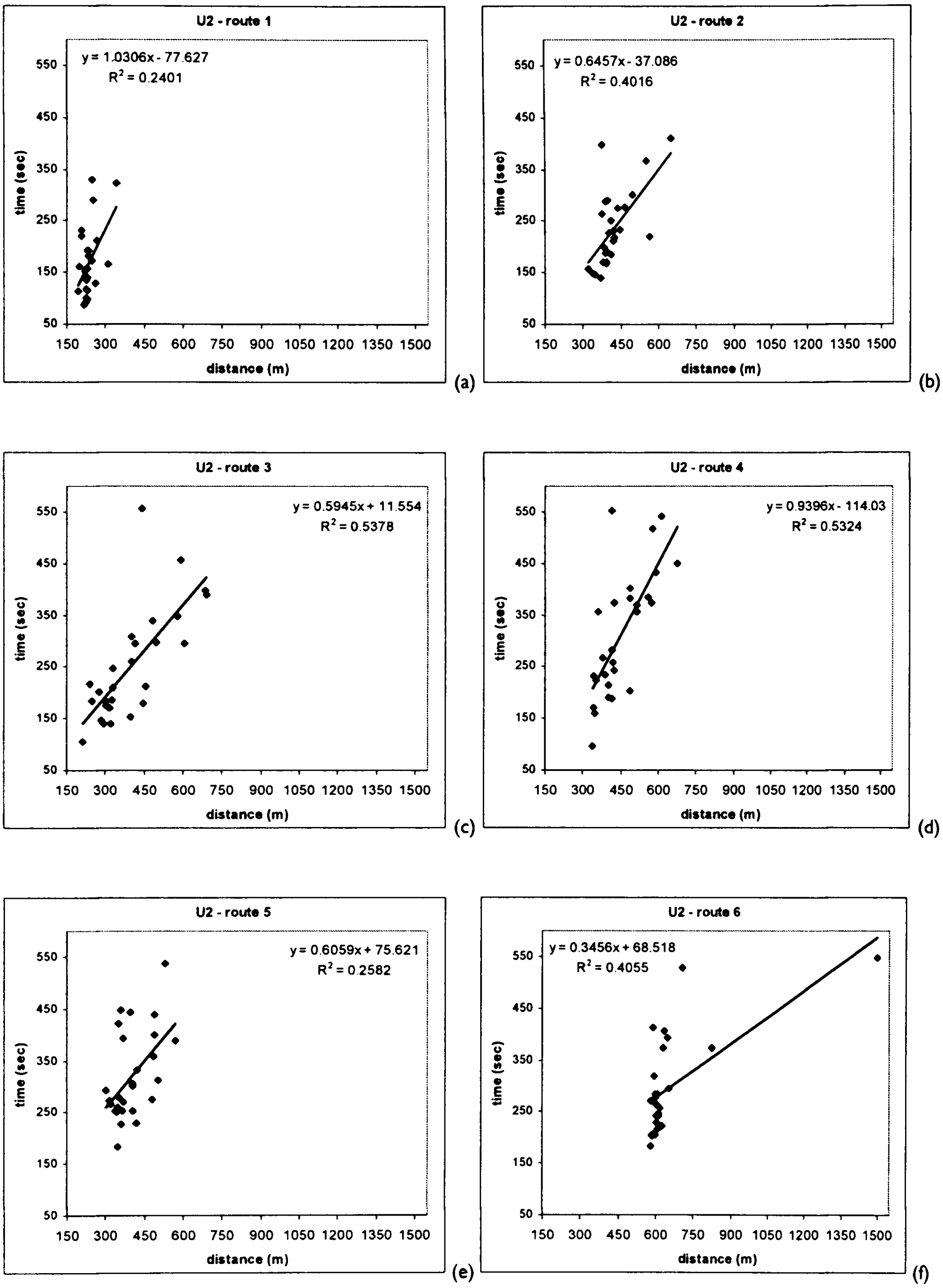


Figure 8.18 Time against distance for six routes in setting U2.

Discussion: In Section 8.4, the distance travelled $D_{travelled}$ and the time taken, $T_{completion}$, are two important factors in performing wayfinding tasks. Both of these variables can reflect the routes taken. The upper speed at which participants can 'walk' through the settings is limited and therefore differences in $T_{completion}$ are more likely to reflect time for accessing information, observing the environment, and time spent being lost or confused. From the observation made of the participants, some do nevertheless access information on the 'fly'. The values of these two variables for all 27 participants in both settings were calculated from the 54 positional track data files discussed in §8.1.1.

For counterbalancing the sequences by which the settings were used in wayfinding experiments, half of the participants started the first set of wayfinding tasks in setting U1, whilst the other half started in setting U2. The test for any significant differences between these two groups was carried out on both sets of variables $D_{travelled}$ and $T_{completion}$ for both settings. The overall results showed that there is no consistent significant difference between these two groups of participants regarding the wayfinding performance as measured by distance travelled and time taken. Thus, for both settings, the sequence in which the settings were used has had no significant influence on the distance travelled and time needed to complete the tasks. Therefore, no significant change arises in learning from the experience of wayfinding in their first setting. In the following analysis, these two groups of participants will therefore be treated as a single group. The apparent lack of any further learning from the wayfinding in the first setting may result from sufficient training in the pre-experiment familiarisation for participants prior to the main experiments (§7.4). This is a positive sign as the data collected reflects participants' unaltered abilities applied to both settings. This is not to argue against any longer term learning effect, but this is beyond the scope of this research. This aspect will be further investigated for PDA information usage time in §8.5.3.

The spatial distribution of the wayfinding tracks taken by all 27 participants is illustrated in two intensity maps (Figure 8.10 for U1, Figure 8.11 for setting U2). Diversity of routes taken for each of the tasks and the different intensities of positional points strongly indicates that the characteristics of spatial locations have a major influence on wayfinding behaviour. The distributions of variables $D_{travelled}$ shown in Figure 8.13 and $T_{completion}$ in Figure 8.15 exhibit differences for each route and appear to vary according to the perceived complexity of wayfinding between successive destinations in the two settings, and the time used for accessing and using information via the PDA. Additionally, the scatter diagrams shown in Figure 8.17 and Figure 8.18 demonstrate the variety of relationships between $D_{travelled}$ and $T_{completion}$ amongst the routes. This also suggests that different wayfinding behaviour is characteristic in areas of different urban morphology (i.e. setting U1 versus setting U2) and in differences in adopting routes which have a range of spatial layouts (route geometry). This will be analysed further in the next Section with respect to the accessing and use of spatial information during wayfinding.

Also illustrated in the intensity maps is that the starting points of each route have high intensities in the figures, which could be explained by more time being spent at these locations prior to moving on. Such periods will have been used to plan the wayfinding strategy. This use of time is particularly noticeable in the scatter diagrams in Figure 8.17(a) and Figure 8.18(a) for Route1 in setting U1 and setting U2 respectively. The descriptive summaries of $T_{completion}$ suggest very similar distances travelled by each participant, but differences in time used for planning (as well as more general familiarisation with the setting) amongst the participants. This period of 'planning time', therefore, should be extracted out from the completion time, $T_{completion}$, to form a new variable which can be studied (see §8.5.4).

The ability to study participants' wayfinding behaviours at these different levels of detail and from different aspects is as a consequence of the data collection methods adopted for carrying out the experiments. In order to examine the interaction between the individual, mobile device and environment, the variables already analysed can be studied alongside the information accessed through the PDA.

8.5 PDA spatial information usage

The access and usage of spatial information via the PDA was collected during participants' wayfinding. In this Section, a range of variables are derived from the integrated data sets to describe individual spatial information usage through the PDA (e.g. frequency of accessing information, time spent on PDA usage, planning time for wayfinding tasks). These variables are then analysed in relation to the spatial layout of the environment in which the wayfinding activities took place as represented in the two urban settings. The term 'PDA information' used in this and subsequent Sections generally refers to all the spatial information accessed through the PDA such as the maps with overview layout of the area, the maps with detailed zoom-in and route descriptions. Also the term 'overview map' refers to the sketch map with correct scaled street layout of the area and selectable landmarks and road names (see §6.2.2), whilst 'detailed map' refers to the zoom-in maps of partial areas (also see §6.2.2). Although the route information was available in both voice and text formats, few participants used voice and therefore both types of information have been grouped as 'route' information. An advantage of the VR environment over 'real world' studies, as will be clear in the following

Sections, is that it is possible to ascertain exactly where, when and for how long participants consult external sources of information, specifically the sources available through the PDA.

8.5.1 Spatial distribution of PDA information access

The spatial distribution of PDA information access can be mapped by using the integrated data sets discussed in §8.1.1. The points where participants accessed and studied PDA information were extracted from these integrated data sets containing positional point data and PDA information usage data. A new data set was then created combining the 27 integrated data tables in setting U1. There are a total of 1,252 points. The intensity map (Figure 8.19) for setting U1 was created in ArcGIS, using kernel density estimation with a 1 metre grid cell and a 10 metre bandwidth. The starting/finishing point and five destinations (D1 to D5) are also shown on the intensity map along with all the road centre lines of the area. Firstly, it clearly demonstrates that the PDA information was frequently used for assisting wayfinding along all routes travelled by participants. The information was accessed and used more frequently on some routes than on others. For instance, the segments of boundary roads in the southern half of the area have lower intensities than the segments of inner roads. This could have resulted from the fact that one side of these boundary roads is lined with homogeneous high trees or hedges (see images in Appendix III), which only gave participants the option of turning into the built-up area for their wayfinding tasks, thus necessitating less frequent recourse to the PDA for information. Secondly, most of higher intensity locations were at the start point of the whole wayfinding experiment and at the destinations of each separate task (which also marked the starting points for the next task). These were usually locations where participants accessed information, in order to plan and determine how they were going to reach the next destination. Thus the greater time spent on these locations led to more positional points being recorded at these locations. However, the intensities at the start points for some routes are higher than others. For example, the densities at D1 and at D2 are higher than those at D4 and at D5. This could have been influenced by the anticipated complexity of the routes to be encountered during the subsequent wayfinding task.

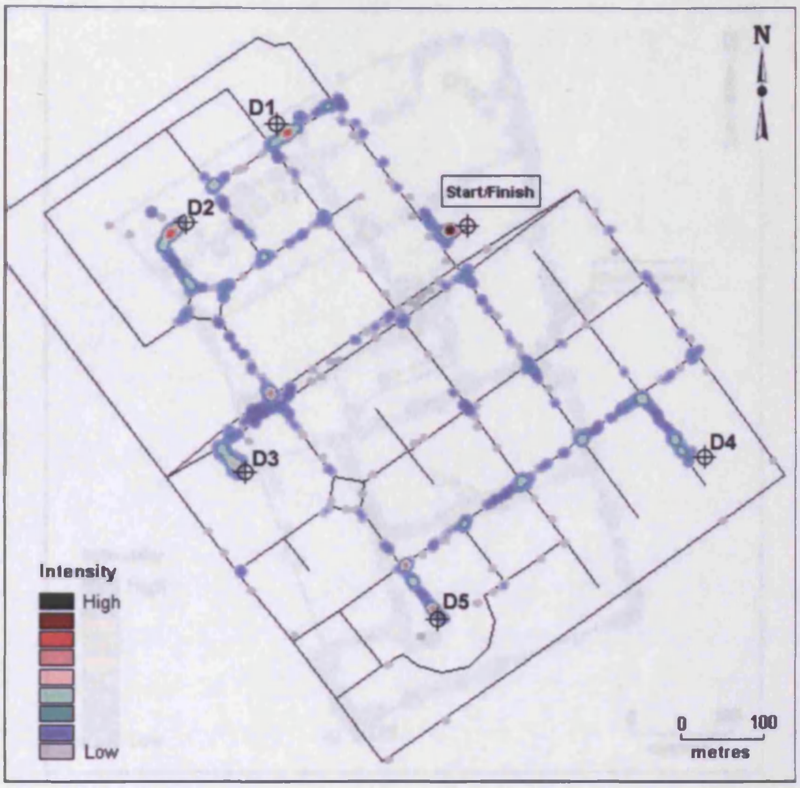


Figure 8.19 Intensity map (number of recorded points per metre^2) of points where PDA information is used - setting U1.

For the setting U2, the same procedure for creating the intensity map was followed using the total of 1,508 position points where PDA information was accessed and studied in setting U2. The intensity map is overlaid on the central road lines of the area with marked start/finish points and the five destination points D1 to D5. Here too the frequent usage of PDA information is evident along all of the travelled routes. All of the starting points of individual wayfinding task are locations with higher intensities, which is consistent with the pattern observed in setting U1. However, in this setting, each of the start points (D1 and D5) demonstrates higher intensities than other locations, more so than in setting U1. This could arise because of the more irregular spatial layout of the area in setting U2 compared with setting U1. The start point for the whole wayfinding experiment in this setting is the location with the highest intensity, correspondingly with the equivalent start point in setting U1. In addition, both sides of the boundary roads in this setting are lined with urban style houses (see images shown in Appendix III). This is different from the boundary road environment in setting U1 (discussed above). This has resulted in a different pattern of PDA information usage along those boundary roads travelled by participants in this setting.

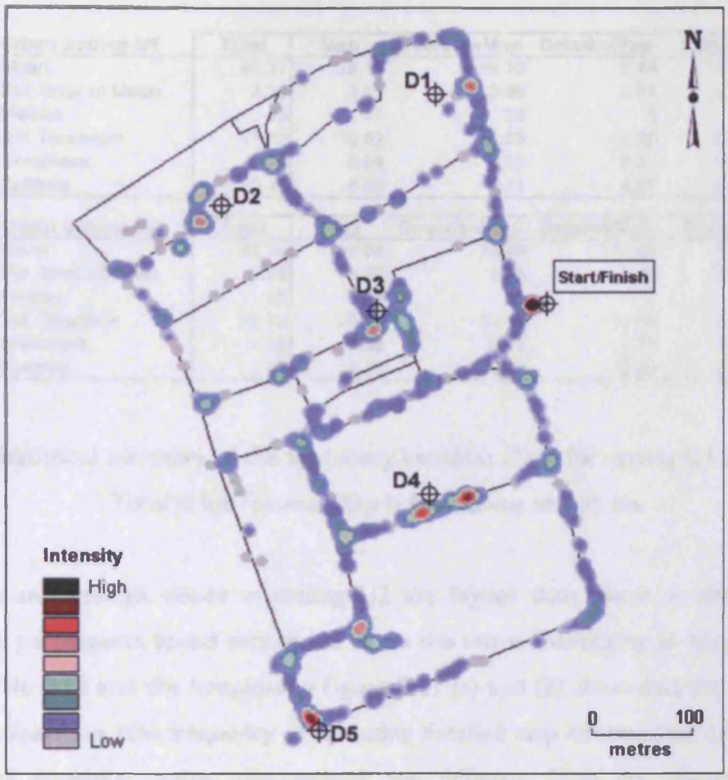


Figure 8.20 Intensity map (per metre²) of points where PDA information is used - setting U2.

8.5.2 Frequency of PDA information access

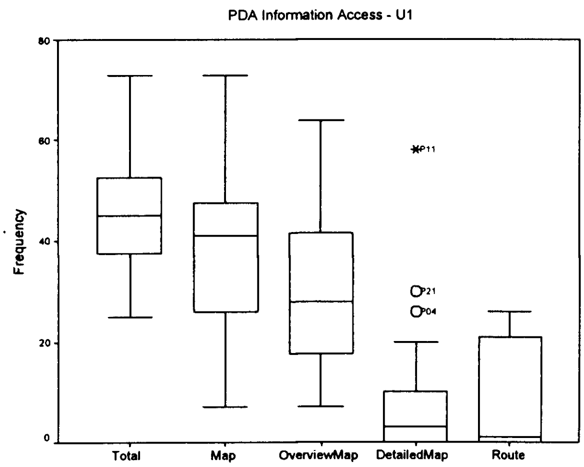
The frequency of PDA information access as a variable, denoted as $F_{pda\text{-}total}$, refers to the numbers of times that the information is accessed using the PDA. This access is both that achieved by means of clicking the PDA for new pages and also referring again to the current page on the PDA. The variable $F_{pda\text{-}total}$ was derived from the action data set (Table 8.1). The variable $F_{pda\text{-}total}$ depicts the frequency of PDA information access for all information. Then a further list of specific frequency variables were derived for accessing all types of maps ($F_{pda\text{-}map}$), accessing overview map only ($F_{pda\text{-}o\_map}$), accessing detailed map only ($F_{pda\text{-}d\_map}$) and accessing route information ($F_{pda\text{-}route}$). The statistical summaries (Table 8.12) show the mean values with the standard deviation for all these frequency variables for both settings U1 and U2. Median value and skewness, kurtosis of the distribution of these variables are also shown in the Table. The boxplots (Figure 21) illustrate these distributions with outlier/extreme values marked.

Urban Setting U1	Total	Map	OverviewMap	DetailedMap	Route
Mean	46.37	38.19	29.70	8.48	8.63
Std. Error of Mean	2.26	3.20	3.09	2.55	2.09
Median	45	41	28	3	1
Std. Deviation	11.72	16.62	16.05	13.23	10.88
Skewness	0.54	0.08	0.53	2.41	0.64
Kurtosis	-0.17	-0.50	-0.41	6.80	-1.52

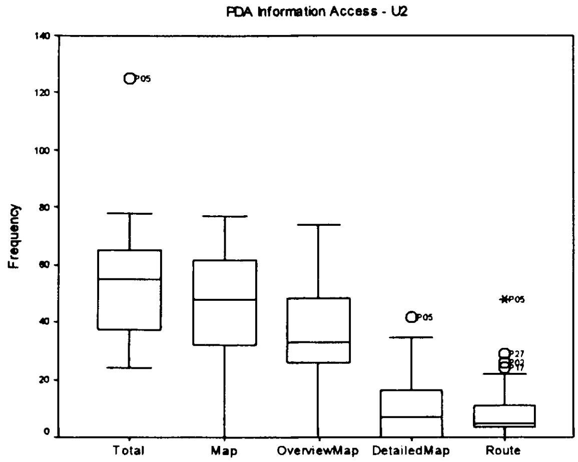
Urban Setting U2	Total	Map	OverviewMap	DetailedMap	Route
Mean	55.74	45.96	35.48	10.48	9.78
Std. Error of Mean	3.99	3.96	3.68	2.32	2.18
Median	55	48	33	7	5
Std. Deviation	20.72	20.57	19.10	12.06	11.32
Skewness	1.26	-0.38	0.32	1.24	1.96
Kurtosis	3.47	-0.67	-0.40	0.69	3.88

Table 8.12 Statistical summary of the frequency variables (F_{pda}) for setting U1 and U2 where Total is for $F_{pda\text{-}total}$, Map is for $F_{pda\text{-}map}$ and so on.

The average and median values in setting U2 are higher than those in setting U1 which suggests that participants found setting U2 to be the more challenging to navigate. Both the figures in Table 8.12 and the boxplots in Figure 8.21 (a) and (b) show that the distribution of the variables $F_{pda\text{-}d\_map}$ (the frequency of accessing detailed map information) and $F_{pda\text{-}route}$ (the frequency of accessing route information) are different from the distribution of the aggregated frequency variable $F_{pda\text{-}total}$ for both settings. There are a number of outlier/extreme values for these two variables. These differences can also be found between these two variables and the variable $F_{pda\text{-}map}$ (the frequency of accessing total map information) and $F_{pda\text{-}o\_map}$ (the frequency of accessing overview map information). The large spread in the distribution of the variables $F_{pda\text{-}route}$ for settings U1 and U2 is evident in both the high standard deviations (Table 8.12) and the boxplots (Figure 8.21(a) and (b)). Also from the boxplots, it can be seen that there is a clear preference for map information as compared with route information.



(a)



(b)

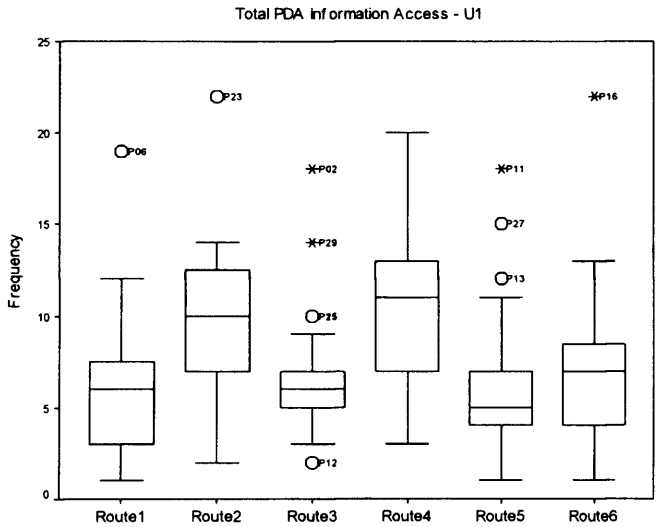
Figure 8.21 Frequency of PDA information accessed (n=27):
(a) setting U1; (b) setting U2.

The frequency variable for total information accessed, $F_{pda\text{-}total}$, was further investigated for each individual task (Route1 to Route6). Table 8.13 shows the statistical summaries of the variable for each route, while Figure 8.22 (a) and (b) illustrates the distribution of these frequency variables for setting U1 and setting U2 respectively. There is considerable variety between the routes with contrasting distributions. This perhaps reflects the relative complexity of each of the routes and the consequent need for consulting the PDA for information. Setting U2 has consistently higher standard deviations suggesting that there is greater range of behaviours given the irregular layout of this setting. Route4 in setting U1 has the highest overall frequency of PDA information access. This corresponds to the time-distance relation shown in Figure 8.17 (d). Although this is the longest route in the U1 experiment, the scatter diagram illustrates how, despite the similar route lengths travelled by participants, proportionately more time was spent on the task (with considerable spread) and is reflected in the higher frequency of PDA access. Overall these results of frequency of PDA access appear to be consistent with the results analysed from completion time $T_{completion}$ and distance travelled $D_{travelled}$.

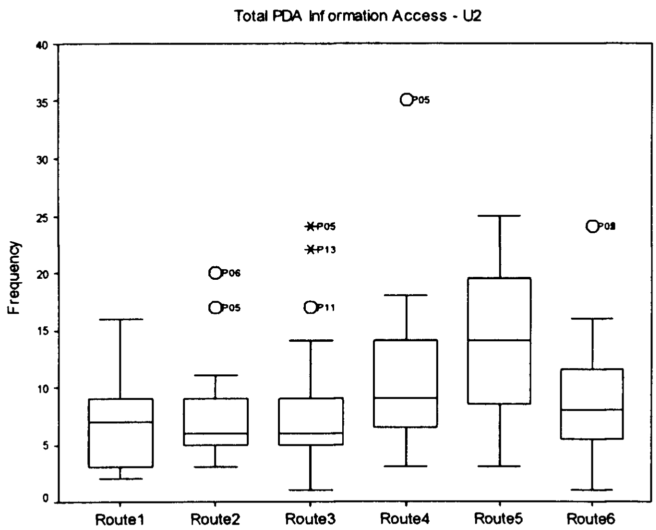
For each of the six routes (Route1 to Route6) in both settings U1 and U2, the statistical summaries and boxplots for each frequency variable, $F_{pda\text{-}map}$, $F_{pda\text{-}o\_map}$, $F_{pda\text{-}d\_map}$ and $F_{pda\text{-}route}$ are shown for reference in Appendix VI.

Urban Setting U1	Total	Route1	Route2	Route3	Route4	Route5	Route6
Mean	46.37	6.00	9.63	6.74	10.63	6.37	7.00
Std. Error of Mean	2.26	0.74	0.77	0.68	0.87	0.77	0.80
Median	45	6	9	6	11	5	7
Std. Deviation	11.72	3.84	4.02	3.51	4.50	3.99	4.15
Skewness	0.54	1.48	0.91	1.57	0.40	1.40	1.83
Kurtosis	-0.17	3.84	2.17	3.19	-0.06	1.86	5.60
Urban Setting U2	Total	Route1	Route2	Route3	Route4	Route5	Route6
Mean	55.74	6.70	7.11	8.22	10.89	13.81	9.00
Std. Error of Mean	3.99	0.79	0.78	1.06	1.28	1.28	1.13
Median	55	7	6	6	9	14	8
Std. Deviation	20.72	4.09	4.05	5.50	6.64	6.63	5.88
Skewness	1.26	0.79	1.80	1.63	1.85	0.03	1.15
Kurtosis	3.47	-0.12	3.61	2.51	5.60	-1.15	1.49

Table 8.13 Statistical summary of the variable $F_{pda\text{-}total}$ (the frequency of PDA information accessed) in total and for each route.



(a)



(b)

Figure 8.22 The frequency of PDA information accessed for each route (n=27): (a) setting U1; (b) setting U2.

The differences in the frequencies of PDA information access between the two groups of participants according to the sequence in which the settings were used have also been tested. The results of the Mann-Whitney U tests are as follows:

- for variable $F_{pda\text{-}total}$ in setting U1: U(14, 13) = 28.5, p = 0.002;
- for variable $F_{pda\text{-}total}$ in setting U2: U(13, 14) = 79.5, p = 0.583.

Thus the H_0 of no significant difference can be rejected at $p < 0.05$ level for setting U1, giving a significant difference in $F_{pda\text{-}total}$ between these two groups of participants. The H_0 of no significant difference cannot be rejected at $p < 0.05$ level for setting U2. By further analysing the differences in each of the six routes (Table 8.14), the majority of routes show that there is no significant difference between the two groups, only one route shows the significant difference at the $p < 0.05$ level. Route 5 (from D4 to D5) in setting U1 is a relatively straightforward wayfinding task (distance travelled and time taken both have a relatively low standard deviation). This route configuration may allow a significant learning effect to be detected in a short-term experiment. Nevertheless, no significant effect can be detected for the other routes. The significant difference for the experiment may be overly influenced by aggregation effects. Therefore, on the basis of this more detailed analysis of each route, the overall differences in $F_{pda\text{-}total}$ do not show any consistently significant change resulting from their experience in their wayfinding in the first setting.

Urban Setting U1	**Route1**	**Route2**	**Route3**	**Route4**	**Route5**	**Route6**
Mann-Whitney U	68	64.5	53.5	87.5	33.5	51.5
Asymp. Sig. (2-tailed)	0.261	0.196	0.061	0.864	0.015	0.056
Exact Sig. [2*(1-tailed Sig.)]	0.28	0.202	0.063	0.867	0.014	0.055

Urban Setting U2	**Route1**	**Route2**	**Route3**	**Route4**	**Route5**	**Route6**
Mann-Whitney U	71	72	68	63	68.5	73
Asymp. Sig. (2-tailed)	0.332	0.356	0.264	0.174	0.275	0.382
Exact Sig. [2*(1-tailed Sig.)]	0.35	0.375	0.28	0.185	0.28	0.402

Table 8.14 Significance test for differences in sequence by individual route.

For urban setting U1 and U2, the mean and median values of the variable $F_{pda\text{-}total}$, as shown in Table 8.11, are higher in setting U2 than in setting U1. This suggests that participants found setting U2 needed more information to complete tasks. However, there is no significant difference from the result of a Man-Whitney U Test:

Total PDA frequency U1 and U2: Mann-Whitney U test: U(27, 27) = 265, p = 0.085;

H_0 cannot be rejected at $p < 0.05$ and there is no significant difference between total PDA frequency between U1 and U2. This result may seem counter-intuitive. However, this may reflect that, in general, the PDA was accessed frequently on all routes travelled despite the two different urban layouts (Figures 8.19 and 8.20). The frequency of usage does not reflect the time used in studying information and the PDA can easily be consulted to re-confirm routes being taken and thereby increasing the frequency of usage. In the next section when the time span of PDA information usage is analysed, the result does show a significant difference between the two settings.

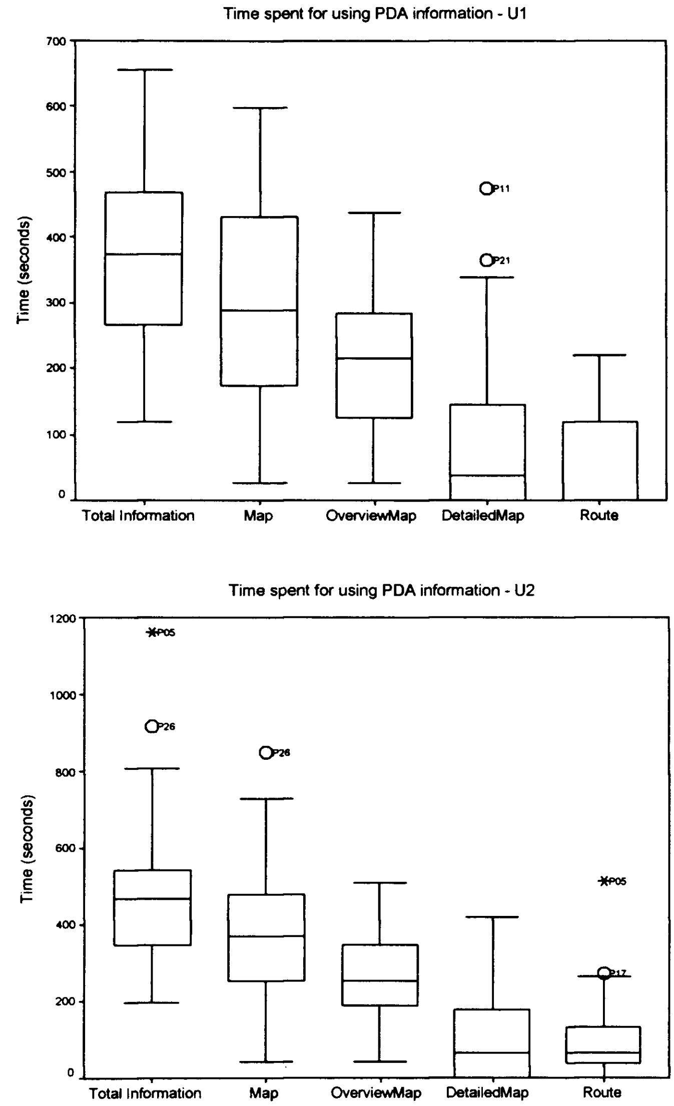
8.5.3 Time spent for PDA information usage

Although the frequency of PDA information accessed provides an important factor in the use of spatial information during the wayfinding tasks, the time spent studying PDA information reflects the different lengths of time used by participants to access and assimilate the information. Furthermore, different lengths of time might be used in studying different types of spatial information (e.g. overview map of the area layout, detailed zoom-in map, route information). The variable of the total time spent for PDA information usage is denoted as $T_{pda\text{-}total}$, comprising the time spent for using all the information through the PDA. The variable $T_{pda\text{-}total}$ was derived from the action data set (Table 8.1). Then some further specific time variables were derived for: using all types of maps ($T_{pda\text{-}map}$), using overview map only ($T_{pda\text{-}o\_map}$), using detailed map only ($T_{pda\text{-}d\_map}$) and using route information ($T_{pda\text{-}route}$). Shown in the statistical summary in Table 8.15, the mean and median values of time are generally higher in U2. When looking at the median time usage, for example, of detailed map $T_{pda\text{-}d\_map}$ it is nearly twice as high in setting U2; use of route information $T_{pda\text{-}route}$ is also correspondingly much higher. Boxplots of the distribution of these variables is shown in Figure 8.23 (a) and (b).

Urban Setting U1	**Total**	**Map**	**OverviewMap**	**DetailedMap**	**Route**
Mean	366.89	307.00	210.63	96.37	59.89
Std. Error of Mean	26.97	29.47	21.92	25.37	14.84
Median	374	289	215	38	0
Std. Deviation	140.15	153.14	113.92	131.81	77.09
Skewness	0.11	0.16	0.39	1.57	0.85
Kurtosis	-0.64	-0.88	-0.64	1.70	-0.80

Urban Setting U2	**Total**	**Map**	**OverviewMap**	**DetailedMap**	**Route**
Mean	487.48	382.00	268.48	113.52	105.48
Std. Error of Mean	39.92	35.48	24.47	24.58	21.96
Median	467	371	254	66	65
Std. Deviation	207.42	184.37	127.16	127.70	114.13
Skewness	1.67	0.52	0.09	1.19	2.11
Kurtosis	3.60	0.64	-0.55	0.50	5.15

Table 8.15 Statistical summary of the time (T_{pda}) variables for settings U1 and U2 where Total is for $T_{pda\text{-}total}$, Map is for $T_{pda\text{-}map}$ and so on.



(a)

(b)

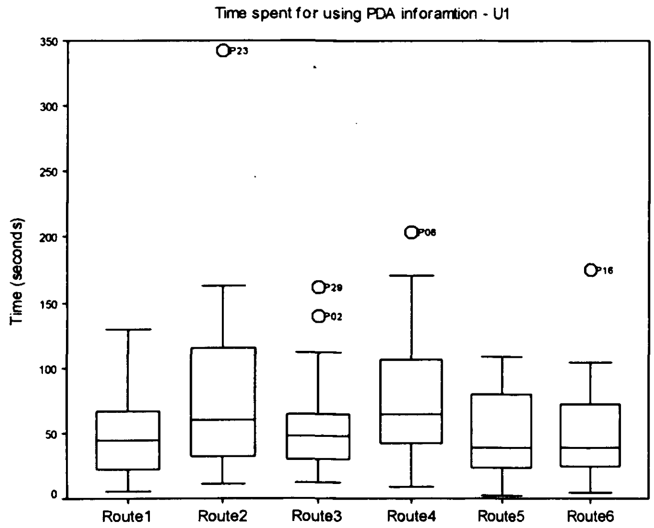
Figure 8.23 Frequency of PDA information accessed (n=27):
(a) setting U1; (b) setting U2.

The time variable for total information usage, $T_{pda\text{-}total}$, was further investigated for each individual task (Route1 to Route6). Table 8.16 shows the statistical summaries of the variable for each route, whilst Figure 8.24 (a) and (b) illustrates the distribution of these frequencies for setting U1 and setting U2 respectively. There is considerable variation between the routes with contrasting distributions. Route4 in setting U1 has the highest overall median time of PDA information access. This corresponds to the time-distance relation shown in Figure 8.17 (d). Route5 in setting U2 has the highest mean and median there, and this too corresponds to the relevant time-distance relation shown in Figure 8.18 (e). This reflects the complexity encountered during this particular task and forms a case study discussed in Section 8.7. Overall these results of the frequency of PDA access appear to be consistent with the results analysed from completion time $T_{completion}$ and distance travelled $D_{travelled}$.

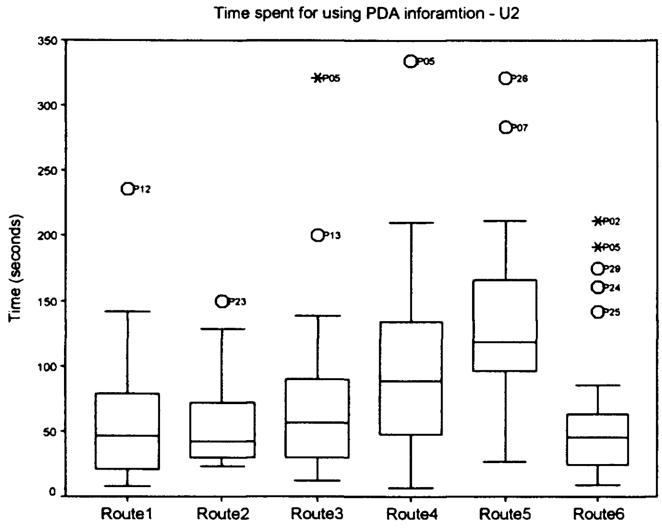
Urban Setting U1	Total	Route1	Route2	Route3	Route4	Route5	Route6
Mean	366.89	48.81	83.81	53.44	78.63	50.22	51.96
Std. Error of Mean	26.97	6.40	13.50	7.08	9.78	6.43	7.47
Median	374	44	60	48	64	39	39
Std. Deviation	140.15	33.23	70.17	36.79	50.84	33.41	38.81
Skewness	0.11	0.81	2.02	1.55	0.90	0.38	1.24
Kurtosis	-0.64	0.12	5.99	2.45	0.07	-1.32	2.40

Urban Setting U2	Total	Route1	Route2	Route3	Route4	Route5	Route6
Mean	487.48	60.67	58.04	73.70	97.70	134.44	62.93
Std. Error of Mean	39.92	10.26	6.63	13.06	13.48	12.98	11.37
Median	467	47	42	56	89	118	45
Std. Deviation	207.42	53.32	34.47	67.86	70.02	67.47	59.09
Skewness	1.67	1.65	1.14	2.20	1.53	1.06	1.46
Kurtosis	3.60	3.20	0.76	6.04	3.84	1.41	0.97

Table 8.16 Statistical summary of the variable $F_{pda\text{-}total}$ (the frequency of PDA information accessed) in total and for each route.



(a)



(b)

Figure 8.24 Time spent for PDA information usage on each route (n=27):
(a) setting U1; (b) setting U2.

For each of the six routes (Route1 to Route6) in both settings U1 and U2, the statistical summaries and boxplots for each frequency variable, $T_{pda\text{-}o\_map}$, $T_{pda\text{-}d\_map}$ and $T_{pda\text{-}route}$ are shown for reference in Appendix VII.

The differences in the time for PDA information access between the two groups of participants according to the sequence in which the settings were used are also tested. The results of the Mann-Whitney U tests are as follows:

- for variable $T_{pda\text{-}total}$ in setting U1: U(14, 13) = 41.00, p = 0.014;
- for variable $T_{pda\text{-}total}$ in setting U2: U(13, 14) = 61.00, p = 0.155.

Thus the H_0 of no significant difference can be rejected at $p < 0.05$ level for setting U1, giving a significant difference in $T_{pda\text{-}total}$ between these two groups of participants. The H_0 of no significant difference cannot be rejected at $p < 0.05$ level for setting U2. Further analysing the differences in each of the six routes (Table 8.17), the majority of routes show that there is no significant difference between the two groups, only Route5 in setting U1 shows a significant difference at $p < 0.05$ level. Therefore the overall differences do not show any consistently significant change in total time spent for PDA usage resulting from their experience in their wayfinding in the first setting.

Urban Setting U1	Route1	Route2	Route3	Route4	Route5	Route6
Mann-Whitney U	77.5	55	56	74	37	52
Asymp. Sig. (2-tailed)	0.512	0.081	0.089	0.409	0.009	0.053
Exact Sig. [2*(1-tailed Sig.)]	0.519	0.085	0.094	0.43	0.008	0.052

Urban Setting U2	Route1	Route2	Route3	Route4	Route5	Route6
Mann-Whitney U	71	72	68	63	68.5	73
Asymp. Sig. (2-tailed)	0.332	0.356	0.264	0.174	0.275	0.382
Exact Sig. [2*(1-tailed Sig.)]	0.35	0.375	0.28	0.185	0.28	0.402

Table 8.17 Significance test for differences in sequence by individual route.

The mean and median values of the variable $T_{pda\text{-}total}$, as shown in Table 8.15, are higher in setting U2 than in setting U1. This suggests that participants found setting U2 to be more challenging to navigate requiring more PDA time. The result of a Man-Whitney U Test:
Total PDA time U1 and U2: Mann-Whitney U test: U(27, 27) = 241.50, $p = 0.033$
shows that the null hypothesis (H_0) can be rejected at $p < 0.05$ with a significant difference between setting U1 and U2. It is therefore the length of time of PDA usage rather than the frequency of PDA usage which differentiates the two urban settings.

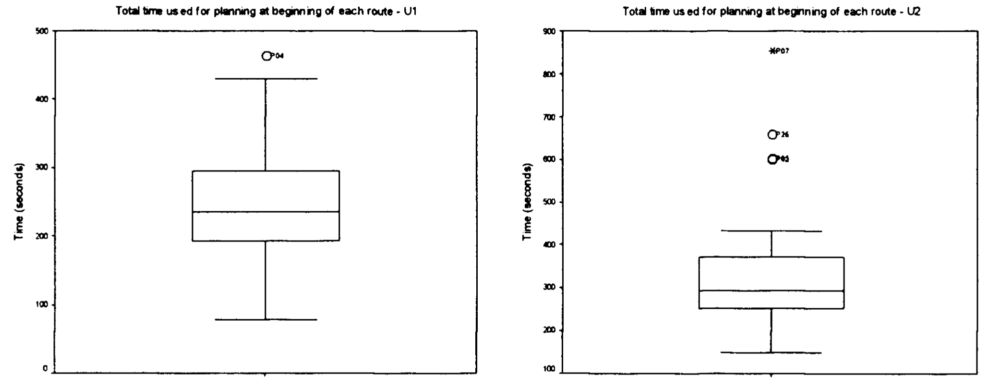
8.5.4 Task planning time

As discussed in §8.4.5 and illustrated in Figure 8.19 and 8.20, the time spent at the start points of each wayfinding task was identified as being used for planning and determining how to reach the next destination. This time could include the time for familiarising oneself with the environment and for accessing and studying the spatial information from the PDA. A new variable is consequently formed here for task planning time, denoted as T_{plan}, which is the time period elapsing while participants plan a new wayfinding task before they actually begin to navigate the chosen route. This variable was calculated from the integrated data sets described in §8.1.1. The variable T_{plan} can be measured as seven variables comprising: $T_{plan\text{-}total}$ for the whole wayfinding experiment; and $T_{plan\text{-}R1}$ to $T_{plan\text{-}R6}$ for each of the six routes. Table 8.18 presents a statistical summary for these seven variables with the column 'Total' for variable $T_{plan\text{-}total}$ and 'Route1 to 'Route6 for variables $T_{plan\text{-}R1}$ to $T_{plan\text{-}R6}$ respectively. The mean and median values of the total planning time ($T_{plan\text{-}total}$) in setting U2 is also higher than in setting U1. The boxplots in Figure 8.25 show the distribution of variable $T_{plan\text{-}total}$ in both settings, where the distribution for setting U2 has a positive skew.

Urban Setting U1	Total	Route1	Route2	Route3	Route4	Route5	Route6
Mean	247.30	43.41	43.93	38.81	43.63	34.81	42.70
Std. Error of Mean	16.80	5.41	6.12	4.36	5.62	4.13	5.34
Median	235	40	33	30	35	33	33
Std. Deviation	87.27	28.10	31.81	22.66	29.21	21.47	27.76
Skewness	0.62	0.73	1.48	1.14	1.20	1.34	1.08
Kurtosis	0.65	0.25	1.94	0.79	1.00	2.57	0.09

Urban Setting U2	Total	Route1	Route2	Route3	Route4	Route5	Route6
Mean	343.67	54.63	40.52	54.89	48.93	102.81	41.89
Std. Error of Mean	31.16	9.21	5.17	7.69	5.80	13.76	6.67
Median	294	42	37	42	45	91	29
Std. Deviation	161.93	47.88	26.84	39.98	30.15	71.52	34.68
Skewness	1.69	2.29	1.13	1.30	0.84	1.06	1.65
Kurtosis	2.93	6.25	1.37	1.14	-0.08	0.64	2.80

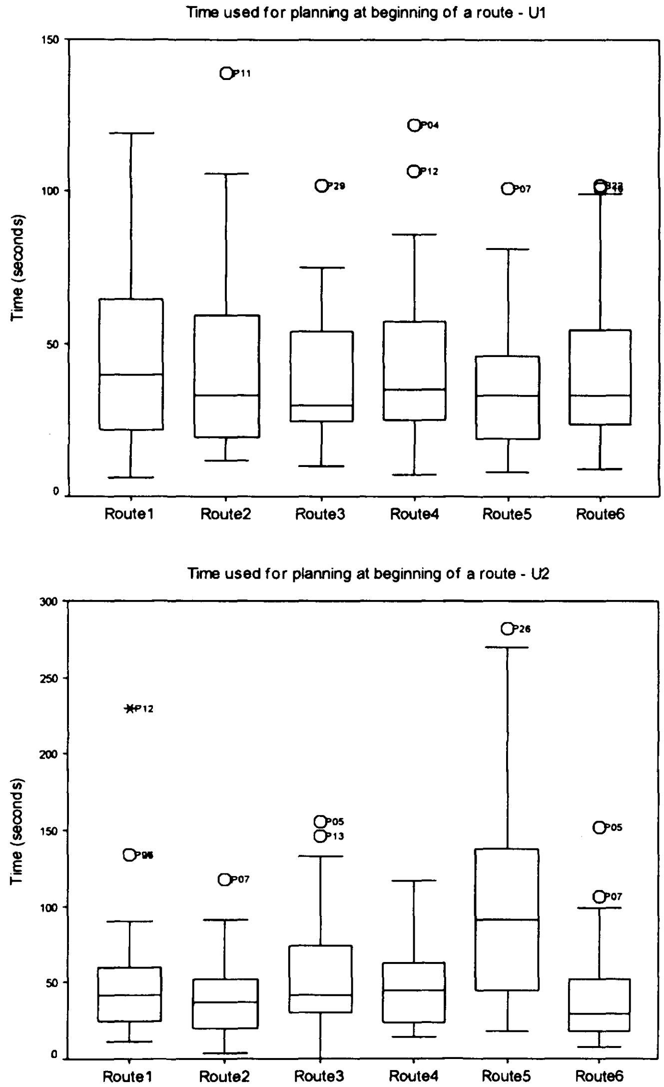
Table 8.18 Planning time for total wayfinding experiment and for the six routes



(a) (b)

Figure 8.25 Total planning time ($T_{plan\text{-}total}$): (a) setting U1; (b) setting U2.

The distributions of the variable $T_{plan\text{-}R1}$ to $T_{plan\text{-}R6}$ for each route in both settings are shown in Figure 8.26. The variability of the distributions is evident across the six routes in both settings. However, the planning time variables in setting U1 have less variability than in setting U2. This could indicate that participants perceived different levels of complexity in the urban morphology of the two settings using the planning time variables.



(a)

(b)

Figure 8.26 Planning time for each route: (a) setting U1; (b) setting U2.

For setting U2, the mean and median of the planning time variable $T_{plan\text{-}total}$ are higher than in setting U1 (Table 8.15). This difference is shown to be significant from the result of the Mann-Whitney U test: $U(27, 27) = 212.00$, $p = 0.008$. Therefore, it is clear that participants spent more time planning in setting U2 than in U1. This further confirms that participants, in general, perceive the setting of the U2 environment as more challenging than U1.

8.5.5 Combining frequency and time of PDA usage

In this Section the relationship of total frequency $F_{pda\text{-}total}$, total time $T_{pda\text{-}total}$ and planning time $T_{plan\text{-}total}$ are investigated. Correlations between the three variables for both settings are given in Figure 8.19. It can be seen that $F_{pda\text{-}total}$ and $T_{pda\text{-}total}$ in both settings have a significant positive correlation in excess of 0.6. $T_{pda\text{-}total}$ also has a significant positive correlation with $T_{plan\text{-}total} > 0.6$. However, $F_{pda\text{-}total}$ and $T_{plan\text{-}total}$ are not significantly correlated.

Urban Setting U1			Tpda-total	Tplan-total
Spearman's rho	Fpda-total	Correlation Coefficient	**0.620**	0.187
N = 27		Sig. (2-tailed)	0.001	0.349
	Tpda-total	Correlation Coefficient		**0.731**
		Sig. (2-tailed)		0.000

Urban Setting U2			Tpda-total	Tplan-total
Spearman's rho	Fpda-total	Correlation Coefficient	**0.653**	0.354
N = 27		Sig. (2-tailed)	0.000	0.070
	Tpda-total	Correlation Coefficient		**0.696**
		Sig. (2-tailed)		0.000

Table 8.19 Correlation matrices (significant correlations $p < 0.05$ in bold).

Ordinary least squares (OLS) regression was carried out between $F_{pda\text{-}total}$ and $T_{pda\text{-}total}$ for settings U1 and U2 with the results given in Figure 8.27 and Table 8.20. Both models are significant at $p < 0.05$. The regression model has a higher R^2 in U2, but this may be influenced by the outlier. In setting U1, the total frequency explains less of the variance in total time of PDA usage. This may relate to differences in the way PDA spatial information is used in setting U1 as compared with setting U2. This is further discussed in §8.7.

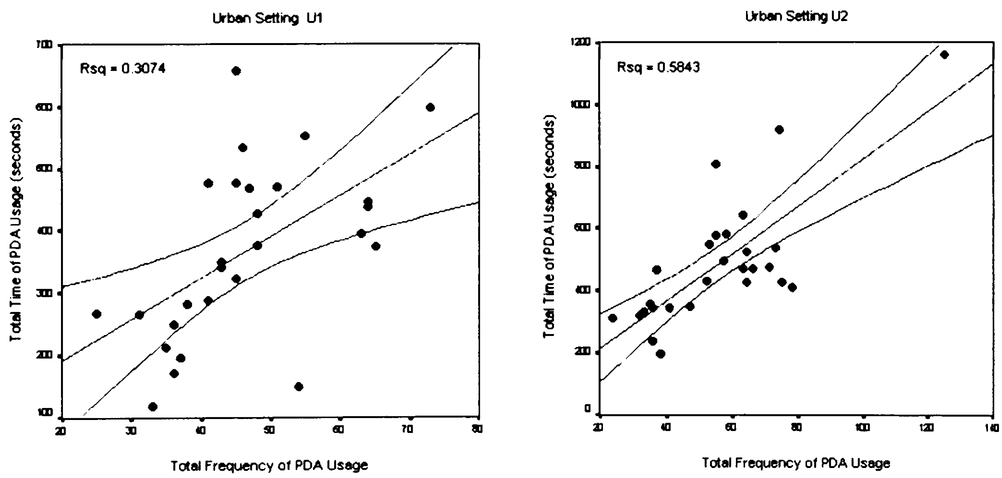


Figure 8.27 Regression models with 95% confidence intervals for $F_{pda\text{-}total}$ against $T_{pda\text{-}total}$ for settings U1 and U2

Urban Setting U1

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
0.554	0.307	0.280	118.940

Predictors: (Constant), $F_{pda\text{-}total}$
Dependent Variable: $T_{pda\text{-}total}$

Urban Setting U2

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
0.764	0.584	0.568	136.379

Predictors: (Constant), $F_{pda\text{-}total}$
Dependent Variable: $T_{pda\text{-}total}$

ANOVA (U1)

	Sum of Squares	df	Mean Square	F	Sig.
Regression	156989.394	1	156989.394	11.097	0.003
Residual	353669.273	25	14146.771		
Total	510658.667	26			

ANOVA (U2)

	Sum of Squares	df	Mean Square	F	Sig.
Regression	653613.578	1	653613.578	35.142	0.000
Residual	464981.162	25	18599.246		
Total	1118594.741	26			

Coefficients (U1)

	Coefficients	Std. Error	t	Sig.
(Constant)	59.576	95.049	0.627	0.536
Fpda-total	6.627	1.989	3.331	0.003

Coefficients (U2)

	Coefficients	Std. Error	t	Sig.
(Constant)	60.923	76.593	0.795	0.434
Fpda-total	7.653	1.291	5.928	0.000

Table 8.20: Regression statistics for $F_{pda\text{-}total}$ and $T_{pda\text{-}total}$ for settings U1 and U2

Similarly, regression has been carried out between $T_{pda\text{-}total}$ and $T_{plan\text{-}total}$ and for settings U1 and U2 with the results given in Figure 8.28 and Table 8.21. $T_{pda\text{-}total}$ only consists the time spent in using the PDA. However, $T_{plan\text{-}total}$ includes time spent using the PDA and time spent observing the environment and deciding the wayfinding strategy. $T_{plan\text{-}total}$ is therefore not an inclusion set of $T_{pda\text{-}total}$. These have higher R^2 values as expected from the correlation matrix. Hence the planning time explains more variance in the total PDA time than the total frequency. Again, setting U2 has the stronger correlation. This also reflects differences in the planning of wayfinding between the two settings.

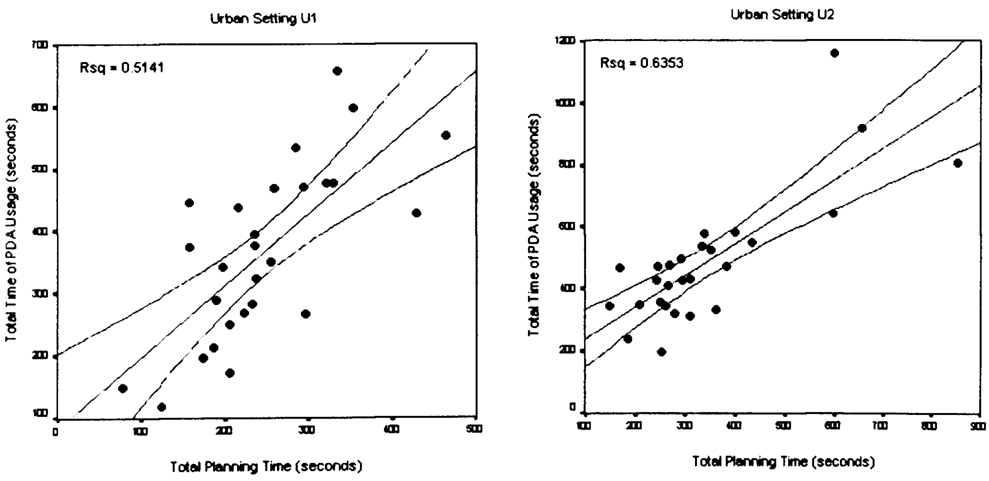


Figure 8.28 Regression models with 95% confidence intervals for $T_{plan\text{-}total}$ and $T_{pda\text{-}total}$ for settings U1 and U2

Urban Setting U1
Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
0.717	0.514	0.495	99.625

Predictors: (Constant), $F_{pda\text{-}total}$
Dependent Variable: $T_{plan\text{-}total}$

Urban Setting U2
Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
0.797	0.635	0.621	127.736

Predictors: (Constant), $T_{plan\text{-}total}$
Dependent Variable: $T_{pda\text{-}total}$

ANOVA (U1)

	Sum of Squares	df	Mean Square	F	Sig.
Regression	262528.943	1	262528.943	26.451	0.000
Residual	248129.723	25	9925.189		
Total	510658.667	26			

ANOVA (U2)

	Sum of Squares	df	Mean Square	F	Sig.
Regression	710680.616	1	710680.616	43.556	0.000
Residual	407914.125	25	16316.565		
Total	1118594.741	26			

Coefficients (U1)

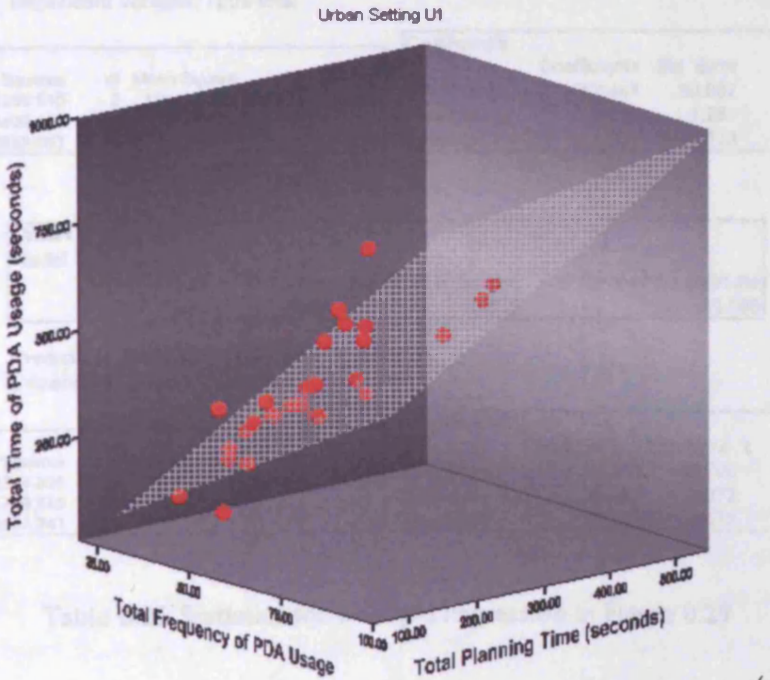
	Coefficients	Std. Error	t	Sig.
(Constant)	82.154	58.589	1.402	0.173
$T_{plan\text{-}total}$	1.151	0.224	5.143	0.000

Coefficients (U2)

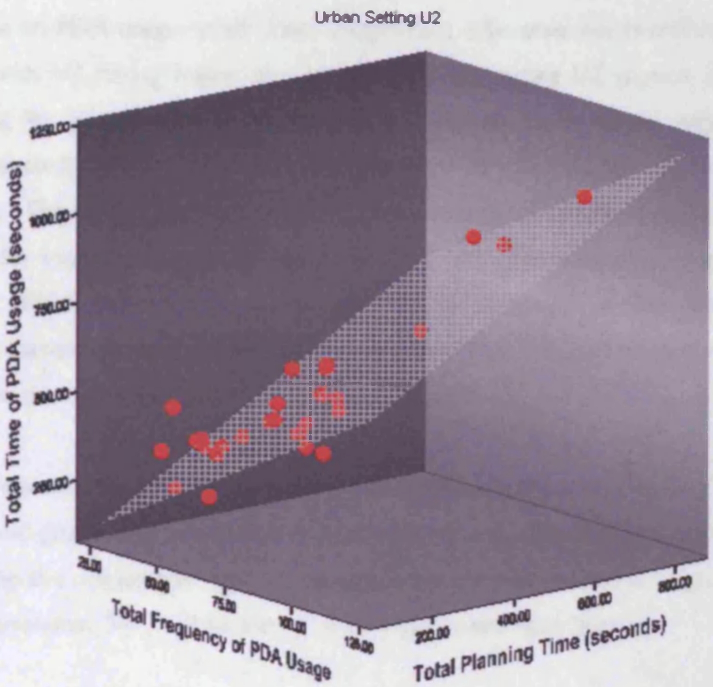
	Coefficients	Std. Error	t	Sig.
(Constant)	136.606	58.574	2.332	0.028
$T_{plan\text{-}total}$	1.021	0.155	6.600	0.000

Table 8.21 Regression statistics for $T_{plan\text{-}total}$ and $T_{pda\text{-}total}$ for settings U1 and U2

Given that $F_{pda\text{-}total}$ and $T_{plan\text{-}total}$ are not significantly correlated, with both correlating well with $T_{pda\text{-}total}$., it was considered possible to construct a multiple regression model for each setting between these two variables and the dependent variable $T_{pda\text{-}total}$. The results are given in Figure 8.29 (a) and (b) and Table 8.22. The results of the ANOVA given in Table 8.22 show that both multiple regression models are significant at $p < 0.001$. Again the R^2 is higher in setting U2 but with both in excess of 0.7. The amount of variance explained is high and therefore $F_{pda\text{-}total}$ and $T_{plan\text{-}total}$ can be taken as the main determinants of $T_{pda\text{-}total}$.



(a)



(b)

Figure 8.29 Multiple regression model (a) for setting U1; (b) for setting U2.

Urban Setting U1
Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
0.854	0.729	0.706	75.939

Predictors: (Constant), Tplan-total, Fpda-total
Dependent Variable: Tpda-total

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	372256.510	2	186128.255	32.276	0.000
Residual	138402.157	24	5766.757		
Total	510658.667	26			

Coefficients

	Coefficients	Std. Error	t	Sig.
(Constant)	-152.448	69.907	-2.181	0.039
Fpda-total	5.590	1.281	4.362	0.000
Tplan-total	1.052	0.172	6.110	0.000

Urban Setting U2
Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
0.923	0.852	0.839	83.099

Predictors: (Constant), Tplan-total, Fpda-total
Dependent Variable: Tpda-total

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	952864.896	2	476432.448	68.994	0.000
Residual	165729.845	24	6905.410		
Total	1118594.741	26			

Coefficients

	Coefficients	Std. Error	t	Sig.
(Constant)	-53.090	49.780	-1.066	0.297
Fpda-total	5.167	0.872	5.922	0.000
Tplan-total	0.735	0.112	6.583	0.000

Table 8.22 Statistics for multiple regression in Figure 8.29

Discussion: In Section 8.5, three main variables have been identified as key descriptors of PDA usage, namely the frequency of PDA information access, the task planning time and the time spent on PDA usage. In all cases, a significant difference was found between settings U1 and U2, with U2 having higher median values. Thus setting U2 appears to have been more challenging for participants. Furthermore, this analysis supports the suggestion that spatial layout and environment along the route do have an influence on frequency of PDA access and usage. This is further supported by the patterns of spatial distribution of PDA usage given in the intensity maps (Figures 8.19 and 8.20). Furthermore, there is evidence that particular routes present participants with specific challenges as reflected in the heightened PDA information access and time spent using the PDA. This will be further explored as part of the case studies in §8.7.

Whilst the preceding analysis has focused on aggregate PDA information usage, as discussed in §8.5.2 and §8.5.3, it is nevertheless important to study the variables on frequency and time spent using the constituent types of information, such as overview maps, detailed maps and route information. This will be further addressed in the next Section.

The sequence in which participants undertook experiments in urban setting U1 and U2 has been further analysed for any effects on PDA information usage that such sequencing might produce. For example, there might be a learning effect which could change the way in which the PDA was being consulted for information (frequency, time). If this was found to be the case, it would be difficult to combine all participants in a single analysis of each setting. The significance tests have shown that there are no consistent differences between participants undertaking the various tasks in a different sequence and therefore all the results for a setting can be studied together. Moreover, this is a positive sign as the data collected reflects participants' unaltered abilities applied to both settings.

From the regression models (Figure 8.29) it can been seen that frequency of PDA access and planning time, when specified as uncorrelated independent variables, have a strong relationship with total PDA usage time. There is, however, a difference between setting U1 and U2 with a higher R^2 goodness of fit in setting U2.

8.6 Classification of individual PDA spatial information usage

The usage of spatial information through consulting the PDA can be quantified using two main categories of variables: the frequency of information access and the time spent for consulting and studying the information. As discussed in the previous Section, there are different types of information which can be accessed and used via the PDA during the wayfinding tasks. To recap, these variables on PDA spatial information transaction are:

- Frequency for total (any) PDA information access – $F_{pda\text{-}total}$
- Frequency for all types of map information access – $F_{pda\text{-}map}$
- Frequency for overview map information access – $F_{pda\text{-}o\_map}$
- Frequency for detailed map information access – $F_{pda\text{-}d\_map}$
- Frequency for route information access – $F_{pda\text{-}route}$
- Time spent on total PDA information usage – $T_{pda\text{-}total}$
- Time spent on all types of map information usage – $T_{pda\text{-}map}$
- Time spent on overview map information usage – $T_{pda\text{-}o\_map}$
- Time spent on detailed map information usage – $T_{pda\text{-}d\_map}$
- Time spent on route information usage – $T_{pda\text{-}route}$

The values of frequency of PDA information access and time spent for PDA information usage include the time spent on accessing information during task planning. Therefore, planning time is not considered separately here. In this Section, analysis of the variables on frequency of access and time spent for each type of information (overview map, detailed map and route information) will be carried out. Patterns of individual preferences for types of information will be derived from this analysis.

For eight out of the ten variables listed above, factor analysis has been used to explore whether the PDA spatial information usage variables can reasonably be reduced to a smaller number of dimensions. The motivation for so doing was to use such dimensions in order to classify individual participants according to their PDA spatial information usage. The variables $F_{pda\text{-}total}$ and $T_{pda\text{-}total}$ were not included in the factor analysis, because the value of these variables sum from the others. However, variables $F_{pda\text{-}map}$ and $T_{pda\text{-}map}$ have been included because, as will become evident from the factor analysis, these two variables do inform patterns of preference over and above what their constituent parts are able to show on their own. Although these may result in an ill-conditioned correlation matrix (Longley, 1967; Mather, 1976), the software (Statistica) handles this by reducing the maximum number of factors that can be extracted. In this analysis, however, the number of factors taken forward is in any case much smaller than the total extracted and the exploratory analysis should be safe.

For the factor analysis, the Kaiser criterion and scree test have been used to select the number of factors which should be retained. Following the Kaiser criterion, the only factors that should normally be retained are those with eigenvalues greater than 1. In other words, only the factors extracting at least as much as the equivalent of one original variable are retained. Therefore, the three factors given in Table 8.23 can be retained because their eigenvalues are all greater than 1. From the scree plot (Figure 8.30), the factors to be retained are normally those above the inflection where the eignevalues level off (the scree). From these two criteria, three factors have been retained. Additionally, the cumulative percentage values of explained variance given in Table 8.23 show that the variance explained by these three factors is 93.948%.

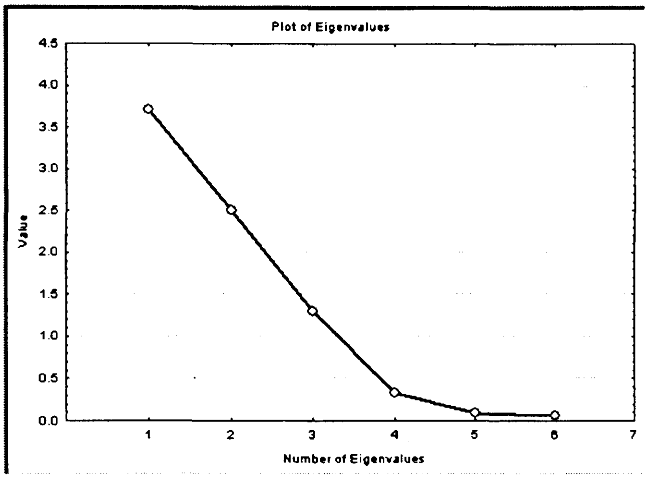


Figure 8.30 Scree plot of Eigenvalues

Eigenvalues
Extraction: Principal components

	Eigenvalue	% Total variance	Cumulative Eigenvalue	Cumulative %
1	3.709	46.362	3.709	46.362
2	2.504	31.297	6.213	77.659
3	1.303	16.289	7.516	93.948

Table 8.23 The Eigenvalues and the percentages of variance explained.

Table 8.24 gives the factor loadings after rotation using Varimax normalisation. Taking the usually accepted cut-off value of > 0.7, it can be seen that the variables with high loadings (>0.7) are mutually exclusive to the three factors. It is therefore straightforward to interpret these factors as follows:

- Factor I is marked by high loadings on variables $T_{pda\text{-}o\_map}$, $F_{pda\text{-}map}$ and $F_{pda\text{-}o\_map}$. This indicates that Factor I is characterised by the usage of the overview map through the PDA both in frequency of access ($F_{pda\text{-}o\_map}$) and time spent on studying such information through the PDA ($T_{pda\text{-}o\_map}$). Furthermore, there is a high loading on the total frequency of PDA map information access ($F_{pda\text{-}map}$). This may reflect the relationship between overview map usage and the total frequency of map information access whereby the usage of the overview map is characterised by more clicking of the PDA to find landmarks and street names.

- Factor 2 is marked by high loadings on variables $T_{pda\text{-}map}$, $T_{pda\text{-}d\_map}$, $F_{pda\text{-}d\_map}$. Thus Factor 2 reveals the usage of the detailed map via the PDA both in time spent studying such information, $T_{pda\text{-}d\_map}$, and the frequency of access, $F_{pda\text{-}d\_map}$. Additionally, there is a high loading on the variable for total time spent on PDA map information usage ($T_{pda\text{-}map}$). This could indicate that detailed map usage is linked to the total time spent for PDA map information usage ($T_{pda\text{-}map}$), but not on the frequency for total PDA map information access ($F_{pda\text{-}map}$). This then differs from Factor 1.
- Factor 3 is marked by high loadings on variables $T_{pad\text{-}route}$, and $F_{pda\text{-}route}$. This factor thus evidently reflects the usage of PDA route information in both frequency of access and time spent in PDA usage for such information.

Factor Loadings (Varimax normalized)
Extraction: Principle Components
(Marked loadings are >.7000)

	Factor 1	*Factor 2*	*Factor 3*
Tpda-map	-0.6471	**0.7113**	0.0966
Tpda-o_map	**-0.9320**	-0.0377	0.1721
Tpda-d_map	0.0261	**0.9861**	-0.0354
Tpda-route	0.1092	0.0676	**-0.9713**
Fpda-map	**-0.8254**	0.4331	0.1868
Fpda-o_map	**-0.9193**	-0.2293	0.2083
Fpda-d_map	0.0525	**0.9751**	-0.0122
Fpda-route	0.2999	-0.0765	**-0.9240**
Explained Variance	2.9189	2.6810	1.9160
Propotin of Total	0.3649	0.3351	0.2395

Table 8.24 Factor loadings on the raw variables.

From the factor analysis results and the discussion above, the three factors extracted from the eight PDA spatial information usage variables, can be regarded as describing three different aspects of the PDA spatial information usage. They are referred as three dimensions of PDA spatial information usage here, denoted as PDA-D1, PDA-D2 and PDA-D3. Dimension PDA-D1 reflects overview map usage with some additional measure of frequency of total PDA map information access, including variables $T_{pda\text{-}o\_map}$, $F_{pda\text{-}o\_map}$ and $F_{pda\text{-}map}$. Dimension PDA-D2 reflects detailed map usage with additional loading on time spent on studying total PDA map information, including variables $T_{pda\text{-}map}$, $T_{pda\text{-}d\_map}$ and $F_{pda\text{-}d\_map}$. The third dimension, PDA-D3, reflects route information usage, including variables $T_{pda\text{-}route}$ and $F_{pda\text{-}route}$. Having thus arrived at a classification of the variables, it is now possible to take this forward to a classification of PDA usage by individuals.

Using the variables in each of the three dimensions, the value of each variable was normalised to [0,1] using a min/max transformation. Three indices were then created by combining the relevant variables giving equal weighting. These three indices were used to derive a classification tree using Ward's method. Four groups have been identified, marked as 1 to 4 in Figure 8. 31. These four groups are denoted as IN-G1 through IN-G4 and are used to represent individual preferences in PDA spatial information usage. The IN-G1 and IN-G2 groups are clearly separated from the rest as shown by the linkage distance in the tree diagram (Figure 8.31); however, it is arguable that IN-G3 and IN-G4 should be combined into a single group. Therefore, further analysis was carried out both in plotting these groups against the three PDA dimensions and in statistical tests.

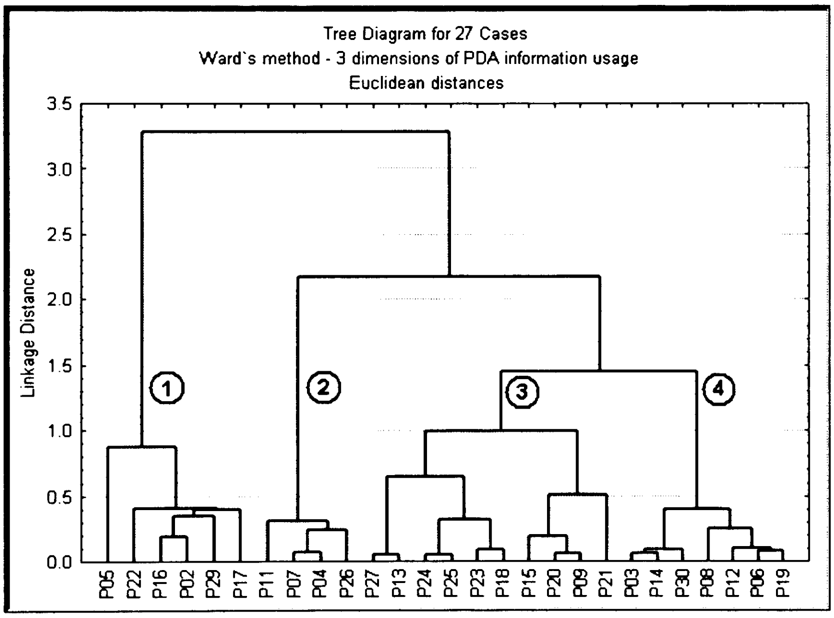
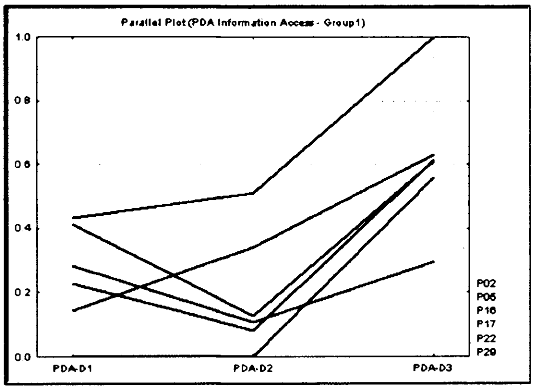
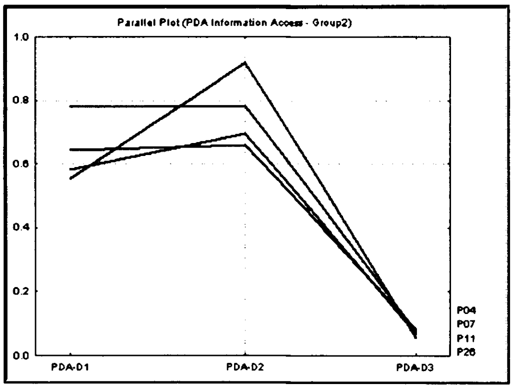


Figure 8.31 Classification tree of individual PDA information usage.

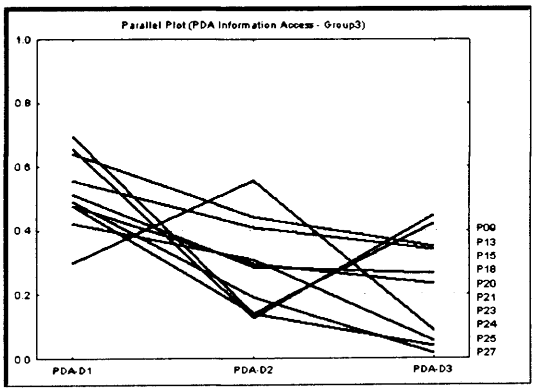
The value of the three indices, representing the three PDA usage dimensions, for all participants in the four PDA spatial information usage groups (IN-G1 to IN-G4) are illustrated using parallel plots. The four groups are shown in Figure 8.32(a), (b), (c) and (d) respectively. As illustrated in these parallel plots, the participants in IN-G1 have much higher scores in the dimension PDA-D3 (PDA route information usage) compared to the other two dimensions within the group. In addition, their scores in the dimension PDA-D3 are also higher than any of the other usage groups. Thus the Group IN-G1 can be concluded as having a pattern of preferring route information to other types of information for their wayfinding tasks. The participants in both groups IN-G2 and IN-G4 have low scores in the dimension PDA-D3. However, participants in IN-G4 Group have much higher scores in the dimension PDA-D1 (overview map information) with much lower scores in the dimension PDA-D2 (detailed map information). The scores in PDA-D1 are also much higher than those of any other usage group. On the other hand, the participants in IN-G2 have high scores on both dimensions PDA-D1 and PDA-D2. These might reflect the ways in which members of Group IN-G2 use both types of map for their wayfinding tasks, or use the overview map to access the detailed maps of particular areas. Finally, the participants in the IN-G3 Group do have slightly higher scores in the dimension PDA-D1 and slightly lower scores in the dimension PDA-D3. Thus, the participant pattern of using PDA spatial information in this group does not seem to show any particular preference for any one type of spatial information. This also confirms that the classification with IN-G3 and IN-G4 as two separate groups is more acceptable than any which might combine them into a single group. Moreover, the distinctive (Figure 8.32(d)) pattern of preferences amongst the members of Group IN-G4 might be difficult to discern in any such combined group.



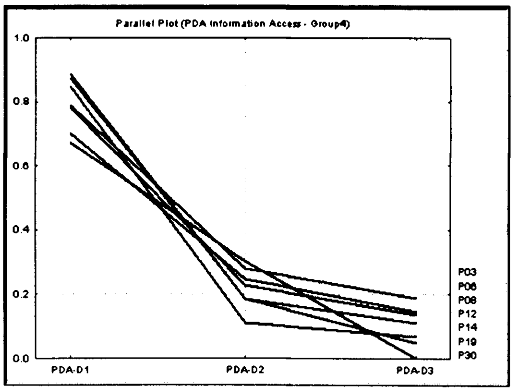
(a)



(b)



(c)



(d)

Figure 8.32 Parallel plots for four PDA spatial information groups:
(a) IN-G1; (b) IN-G2; (c) IN-G3; (d) IN-G4.

Kruskal-Wallis tests were carried out for the four PDA spatial information usage groups. These four groups are all significantly different at $p < 0.05$ with regard to the three underlying variables (Table 8.25), reinforcing the conclusion that the classification of individual PDA usage into four groups is sound.

Dimension	*Kruskal-Wallis test result*
PDA-D1	H (3, N= 27) =20.698 p =.0001
PDA-D2	H (3, N= 27) =11.787 p =.0082
PDA-D3	H (3, N= 27) =13.656 p =.0034

Table 8.25 Statistical tests for the four groups IN-G1 to IN-G4

The four PDA spatial information usage groups (abbreviated here as PDA information usage, or just PDA usage) were also cross tabulated with participant self-assessments of spatial abilities (SA) using the groups SA-G1 to SA-G3 (Table 8.26). These SA groups were derived from the analysis of self-assessed spatial ability scores, which were discussed in §8.2. The figures in Table 8.26 show the numbers of the participants falling throughout the cross classification. At first glance, there appears to be no strong match between these two types of groups. However, the general tendency shows that the majority of the participants in SA-G3 (with higher self-assessed spatial ability scores) have preferences for map-oriented spatial information, whilst participants in SA-G2 use a range of spatial information. Interestingly, nearly half of the participants in SA-G1 (with low self-assessed spatial ability scores) have preferences for route information, while the remainder prefer the mixture of route and map information form the overview maps. The numbers of participants in the four PDA spatial information usage groups have also been compared with the numbers of participants in the three groups with tendencies for route, landmark and map thinking (TK-Groups) TK-G1 to TK -G3 (Table 8.27). These TK groups were derived from the analysis of self-assessed spatial ability scores, (§8.2.2). Again, although there is no simple match between these two groups, the numbers of the participants in TK-G1 (with a self-assessed tendency for map and landmark thinking) all fall into the PDA usage groups IN-G2 to IN-G4, which have strong preferences on the map information usage. However, the participants in TK-G2 (with a self-assessed tendency for route and landmark thinking) are split between the Group IN-G1 (route information usage) and the Group IN-G3 (mixed spatial information usage). Because of the small numbers falling into each category in the crosstables, no statistical tests have been carried out.

	PDA-Usage			
SA-Group	IN-G1 (route)	IN-G2 (detailed map)	IN-G3 (mixed)	IN-G4 (overview map)
SA-G1 (low score)	3	0	1	3
SA-G2 (intermediate score)	1	1	5	
SA-G3 (high score)	2	3	4	4

Table 8.26 Crosstabulation of observed PDA usage and self assessment of spatial ability (SA).

TK-Group	*PDA-Usage* IN-G1 (route)	IN-G2 (detailed map)	IN-G3 (mixed)	IN-G4 (overview map)
TK-G1 (map + landmark)		3	2	6
TK-G2 (route + landmark)	4	1	5	1
TK-G3 (all)	2	0	3	0

Table 8.27 Crosstabulation of observed PDA usage and tendency for route, landmark and map thinking (TK).

Discussion: In this Section, a range of variables on the usage of spatial information by consulting the PDA have been classified into three dimensions using factor analysis. These three dimensions, PDA-D1 to PDA-D3, can be identified relating to route information usage, overview map usage and detailed map usage. The four resultant PDA spatial information usage groups, IN-G1 to IN-G4, have been established by means of a classification tree based on the three PDA dimensions (Figure 8.31). From the parallel plots (Figure 8.32), the different patterns between these four groups show that there are clear preferences in types of spatial information used by individuals during their wayfinding tasks. The participants in Group IN-G1 have a preference for route information during wayfinding tasks. Members of the Group IN-G4 have strong preference for overview maps of the area over other types of information. This group also uses (IN-G4) overview maps in association with landmark information. The access of landmark information by clicking on the overview map may be manifest in the frequency of total PDA map information ($F_{pda\text{-}map}$) scores, which is one of the underlying variables in PDA-D1 (overview map usage). The participants in Group IN-G2 have a preference for detailed maps over route information. The preference for overview maps is also evident amongst the members of this group. This could result from the ways in which detailed map information is accessed through the initial display of an overview map. However, the participants in this Group (IN-G2) tend to have their main preference as using detailed maps. The variable $T_{pda\text{-}map}$, which is one of the underlying variables in PDA-D2 (detailed map usage), reflects the time spent on studying PDA map information. In other words, high scores in PDA-D2 could also be indicative of greater time spent studying detailed PDA maps. Furthermore, the figures shown in the crosstable (Table 8.26), suggest discernible relations between self-assignments of spatial ability groups (SA groups) and observed PDA spatial information usage (IN groups). Similarly, trends can be identified between assignments to the four IN groups and the three TK groups (tendency for route, landmark and map thinking). The self-assessed SA groups and TK groups, therefore, may provide a useful means of understanding preferences for spatial information usage. However, there is not a clear relationship. The four individual PDA groups, established through the three PDA dimensions from measured activities, do have a clear pattern in preferences in PDA spatial information usage.

8.7 Case studies

In the preceding Sections, a range of variables has been elicited from the empirical data to describe and measure wayfinding behaviour and PDA spatial information usage. Analyses have been carried out to investigate these variables in relation to the two different urban settings and the three different self-assessed spatial ability groups. Furthermore, a classification has been established based on the individual PDA spatial information usage. In §8.7.1, group level case studies of three self-assessed spatial ability (SA) groups and the four PDA information usage (IN) groups are presented in respect of spatial layout and spatial information usage. In §8.7.2, individual level case studies are examined, largely qualitatively, in respect of spatial information usage, wayfinding strategies and spatial knowledge recall. These cases concerns eight individuals picked from different SA and IN groups.

8.7.1 Case studies: group level

The first group level study is of the three spatial ability groups (SA-G1, SA-G2 and SA-G3) which have been derived from the analysis of self-assessed questionnaire responses (see §8.2.2). To recap, SA-G1 is low self-assessed spatial ability group, SA-G2 suggest intermediate self-assessed spatial ability and SA-G3 suggest high self-assessed spatial ability. The intensities of the wayfinding position track points were mapped for the participants in these three groups for both settings U1 and U2, as shown in Figures 8.33 to 8.35. These intensity maps were created using kernel density estimation with 1 metre cell size and 10 metre bandwidth. Although the method used is the same as the one used to illustrate the spatial distribution for all participant tracks (Figure 8.10 and Figure 8.11), it is also possible to map similar distributions for the different spatial ability groups. In these maps, higher intensity locations show where participants move less or dwell for prolonged periods. Low intensities are where participants spend less time. In a similar way to the analysis carried out in previous Sections on the variables which describe wayfinding behaviour and PDA information usage, the patterns shown in these intensity maps can be used to identify differences in wayfinding behaviour between the three groups.

Before investigating the intensity maps of wayfinding tracks, the differences between the three spatial ability groups were tested in respect of two variables: distance travelled ($D_{travelled}$) and time taken for completion ($T_{completion}$). These two variables were discussed in §8.4 as two factors describing wayfinding performance. The results from Kruskal-Wallis tests show that there is a significant difference ($H(2,27)=10.300$, $p=0.006$) between the three groups for setting U1 with respect to the distance travelled: however, there is no significant difference between them with respect to time taken for completion. From the distribution of variable $D_{travelled}$ shown in Figure 8.33, the participants in SA-G2 and SA-G3 have a high median value of $D_{travelled}$, whilst the participants in SA-G1 have low median values of $D_{travelled}$. This might reflect that the participants from SA-G2 and SA-G3 were able to exercise more diversity in their route choices in setting U1. Nevertheless, they did not spend more time in completing the wayfinding tasks. This is confirmed in the discussion below. There is no significant difference between the three SA groups in settings U2 with respect of $D_{travelled}$ and $T_{completion}$.

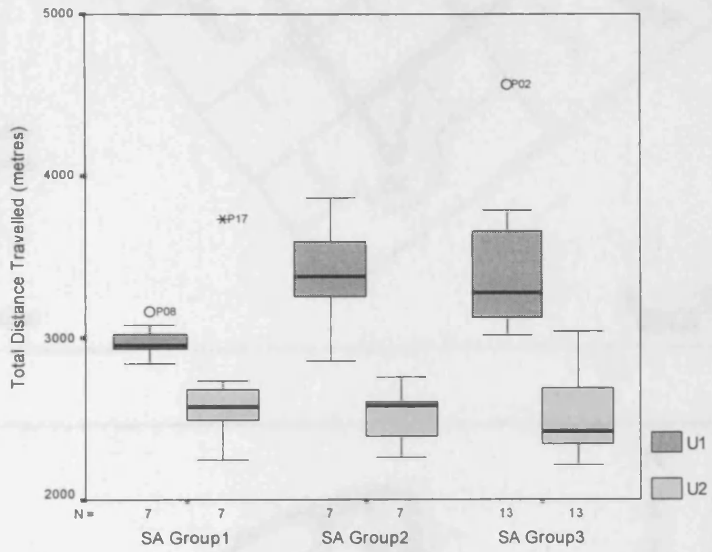
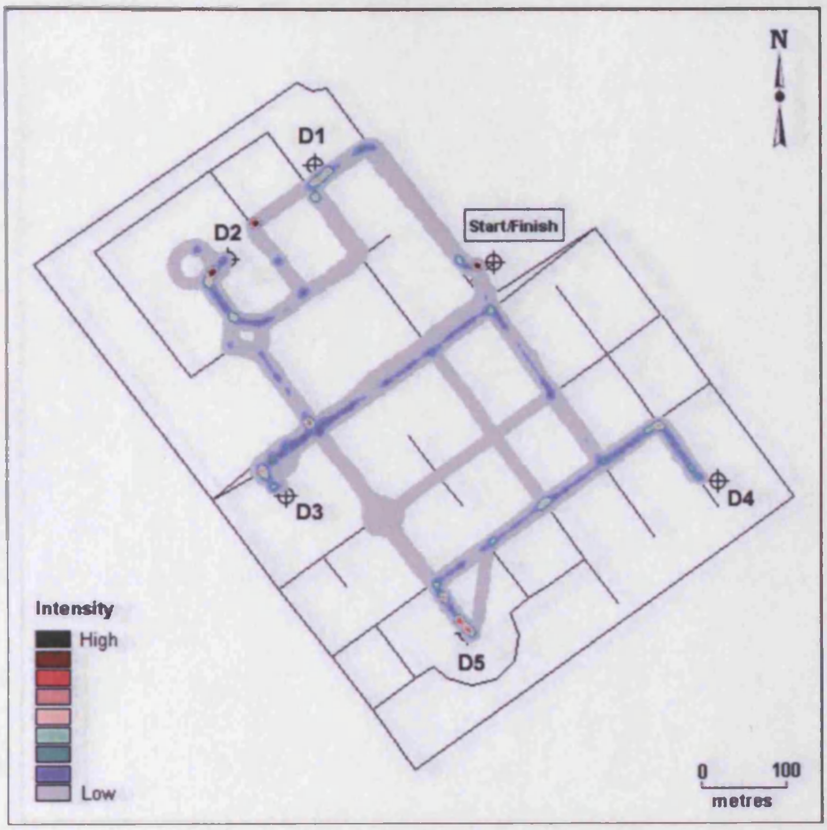
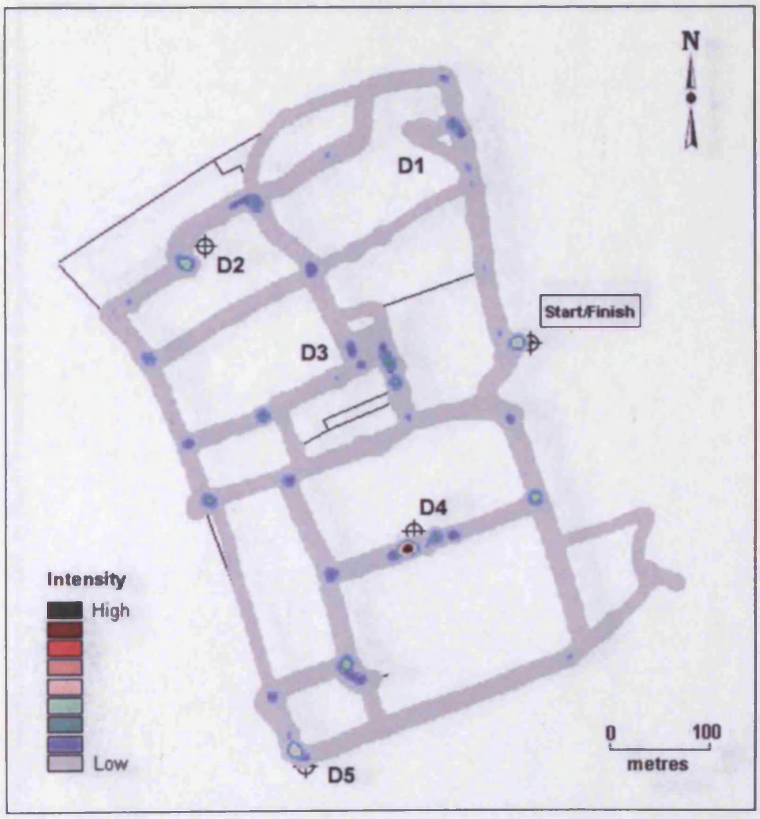


Figure 8.33 Boxplot of variable $D_{travelled}$ for three SA groups in settings U1 and U2

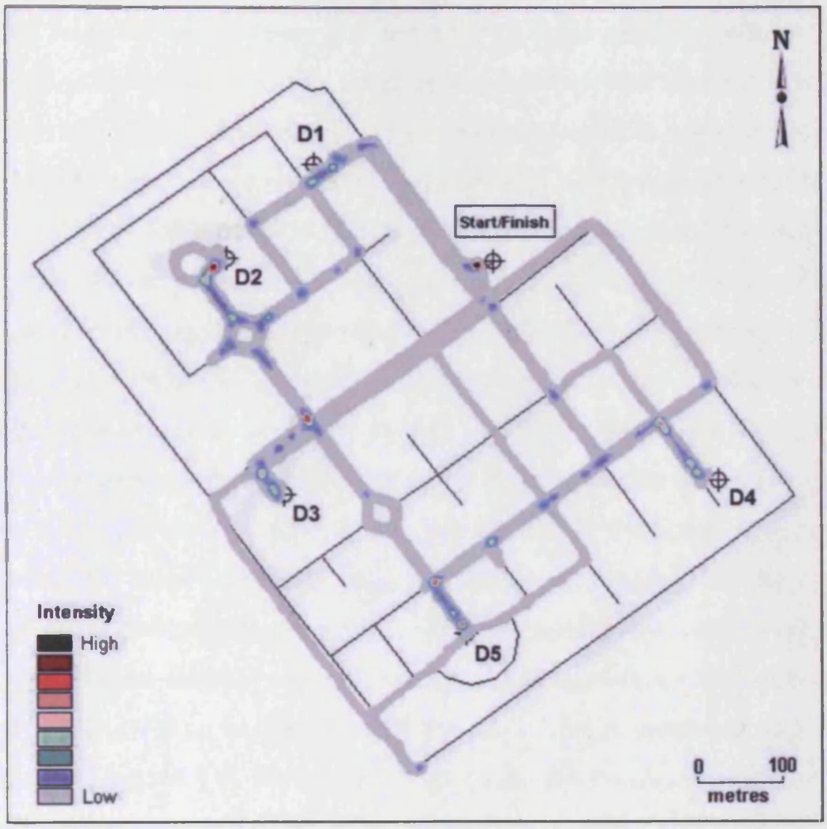


(a)

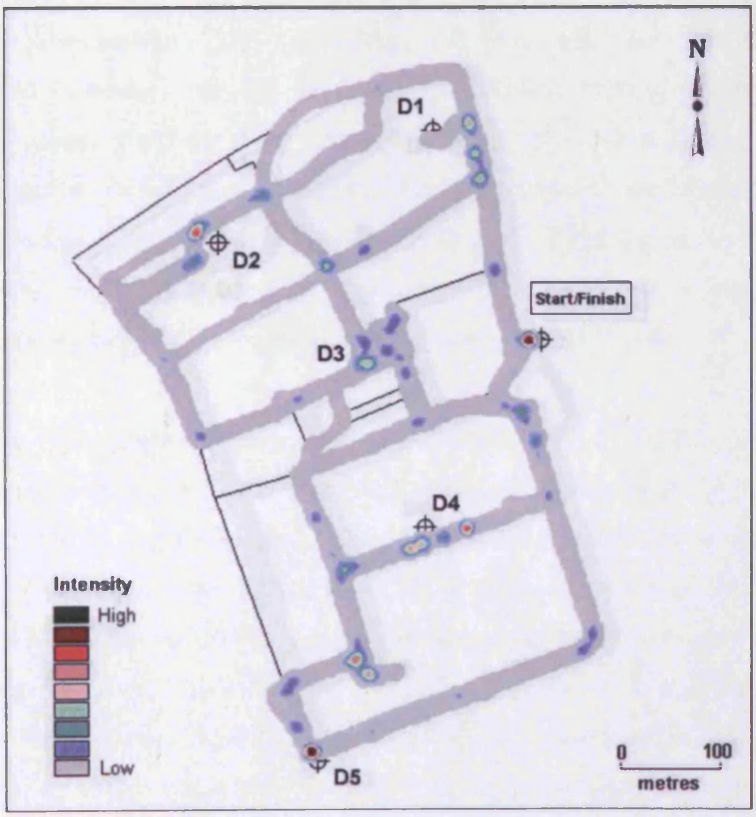


(b)

Figure 8.34 Intensity maps for self-assessed spatial ability Group SA-G1 (low score): (a) setting U1; (b) setting U2.



(a)



(b)

Figure 8.35 Intensity maps for self-assessed spatial ability Group SA-G2 (medium score): (a) setting U1; (b) setting U2.

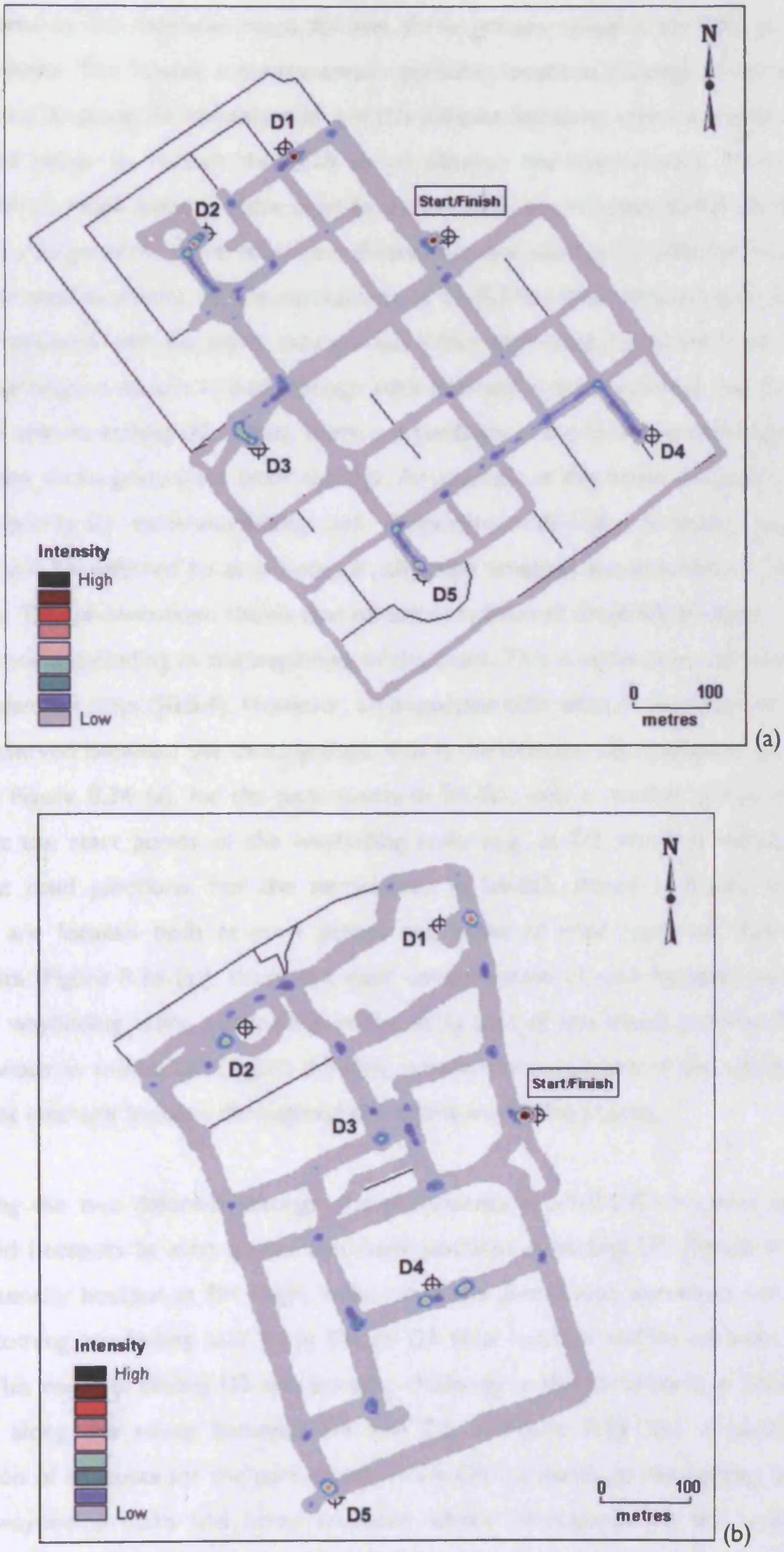


Figure 8.36 Intensity maps for self-assessed spatial ability Group SA-3 (high score): (a) setting U1; (b) setting U2.

The patterns in the intensity maps for the three groups reveal a number of differences between them. The lowest intensity areas represent locations through which participants pass without stopping. All intensities above this indicate locations where participants stopped or lingered either to consult the PDA or to observe the environment. Thus apart from showing which route options were used by participants, any intensity above the lowest is of interest. To begin with, there is greater diversity in the number of different routes chosen (out of the total available) by the participants in SA-G3 for their wayfinding (Figure 8.36 (a) and (b)) compared with the other two groups. When observing this diversity across the two different settings, it occurs in both though such diversity is demonstrated more obviously in setting U1 than in setting U2. Next, there is a similarity in the locations with higher intensity amongst the three groups for both settings. An example is the higher intensity locations at the start points for each wayfinding task. A location with higher intensity (above lowest intensity) will be referred to as a 'hotspot', although hotspots themselves can have different intensities. This phenomenon shows that participants from all three SA groups spent time for planning their wayfinding at the beginning of the tasks. This is consistent with the analysis of the task planning time (§8.5.4). However, an important difference in the patterns of hotspots can be observed between the three groups, that is the different distribution of such hotspots. Shown in Figure 8.34 (a), for the participants in SA-G1, only a number of the hotspots are located at the start points of the wayfinding tasks (e.g. at D2 and D5) whilst others are located at road junctions. For the participants in SA-G2, shown in Figure 8.35 (a), the hotspots are located both at start points and some of road junctions. But for SA-G3 participants (Figure 8.36 (a)), there is a clear concentration of such hotspots at the starting points of wayfinding tasks, particularly in the early part of the entire journey. This is even more obvious in setting U2 (Figure 8.36(b)), where the start point of the whole journey is the highest intensity location throughout the entire wayfinding routes.

Comparing the two different settings, the participants in SA-G1 Group have more evenly distributed hotspots at start points and road junctions in setting U2 (Figure 8.34(b)). The higher intensity hotspot at D4 might reflect that the participants perceived some challenge for the coming wayfinding task from D4 to D5 (this location will be analysed in detail in §8.7.2). This route in setting U2 also posed a challenge to the participants in SA-G2 (see the hotspots along the route between D4 and D5 in Figure 8.35 (b)). In setting U2, the distribution of hotspots for the participants in SA-G2 are mainly at the starting points of the various wayfinding tasks and some locations where participants felt the need for more information. The route D4 to D5 in setting U2, which appears to be a challenge to the participants in SA-G1 and SA-G2, does not cause such high intensity hotspot for the participants in SA-G3 (Figure 8.36(b)).

The three spatial ability groups are further investigated in terms of the frequency of being lost or confused. These frequency data were elicited from the individual wayfinding track position data and observation data based on the number of time participants were lost and/or confused. The track position data can show behaviour consistent with being lost (such as taking an obvious wrong turning, overshoot and turning back) or confused (such as dwelling at points of choice not knowing where to go). The observation data also recorded such incidences either from the investigator direct observation or from participants' own admissions. As shown in the Figure 8.37, the frequency of being lost or confused for the participants in SA-G1 is higher in setting U2 than in setting U1. The participants in SA-G2 and SA-G3 performed more consistently in both settings in terms of the number of times that they were lost or confused. In other words, the difference between urban settings has greater effect upon participant wayfinding performance in SA-G1 than for participants in the other groups. Kruskal-Wallis tests show that there is a significant difference between the three groups in setting U1 in respect of the frequency of being lost or confused, $H(2,27) = 9.006$ $p = 0.011$, but not in setting U2, $H(2,27) = 1.300$ $p = 0.522$.

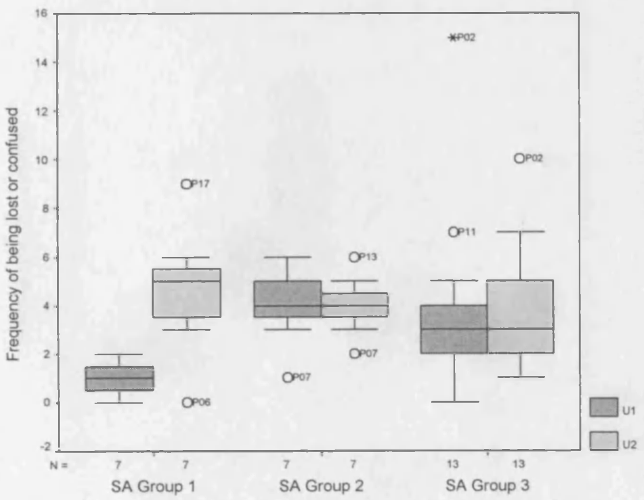


Fig 8.37 Frequency of being lost or confused for three SA groups in settings U1 and U2

The second case study here is of the four PDA spatial information usage groups, which were classified based on the three indices derived from a range of PDA information usage variables (see §8.6). To recap, these four groups are: Group IN-G1 with route information oriented usage; Group IN-G2 with map oriented usage with clear preferences for detailed maps; Group IN-G3 with mix mode of information usage; and Group IN-G4 with map oriented usage and clear preferences for overview maps.

To begin with, statistically, there is no significant difference between these four groups in terms of distance travelled or time taken for completing wayfinding tasks. However, the time used for task planning shows a significant difference, at $p < 0.05$ level, between the four groups in setting U1, but not in setting U2: setting U1 H(3, N=27) = 10.688 $p = 0.014$; setting U2 H(3, N=27) = 7.584 $p = 0.055$. As shown in Figure 8.38, the participants in information usage Group IN-G2 have highest values for total planning time ($T_{plan\text{-}total}$) compared with the other groups. When in setting U2, there appears to be a greater range in $T_{plan\text{-}total}$ amongst the participants in this group. This appears to have been caused by the more irregular layout of setting U2 giving participants additional challenges in planning their routes, predominantly using detailed maps. Furthermore, the influence of the setting has a much less marked effect on $T_{plan\text{-}total}$ for groups IN-G1 and IN-G3, which are the route information usage and mix mode information usage groups. The settings do appear to have an influence on the median value of $T_{plan\text{-}total}$ for the participants in IN-G4 which is the overview map information usage group, setting U1 requiring this group to spend less time for planning.

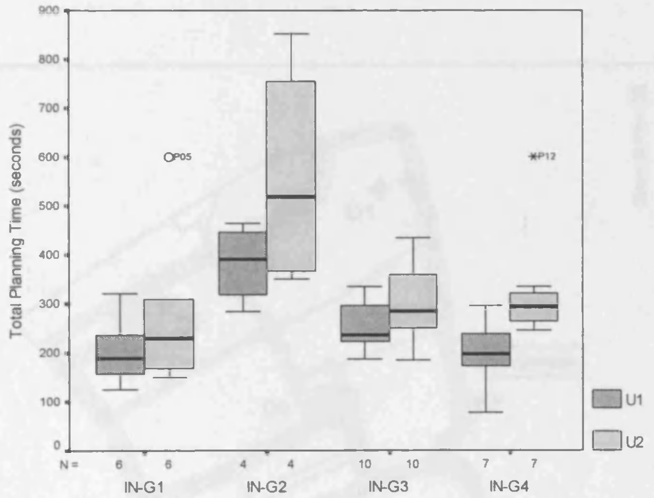
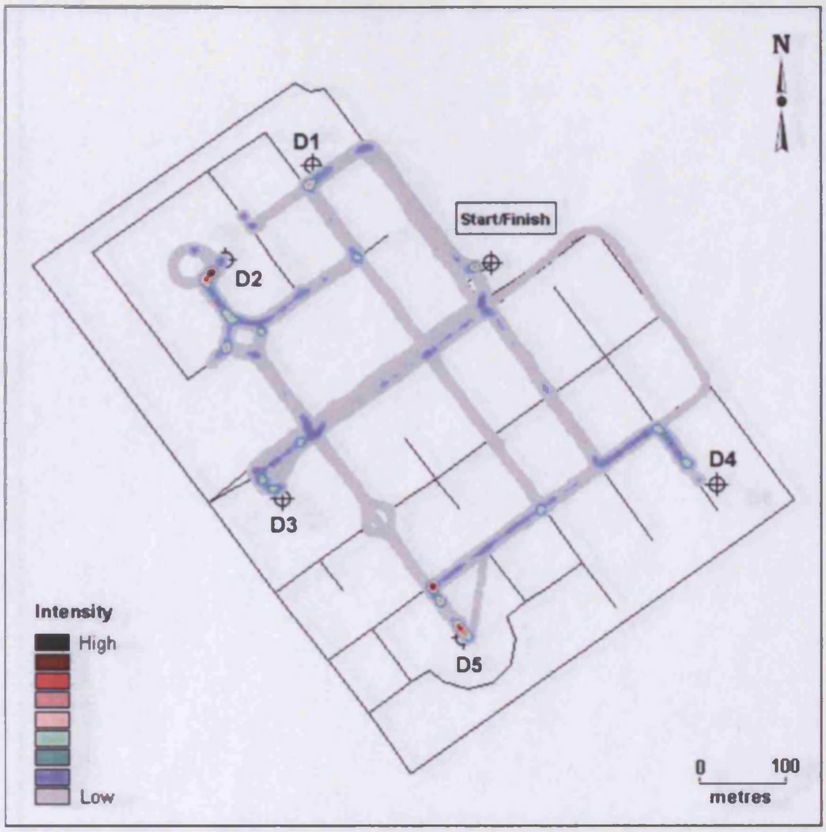
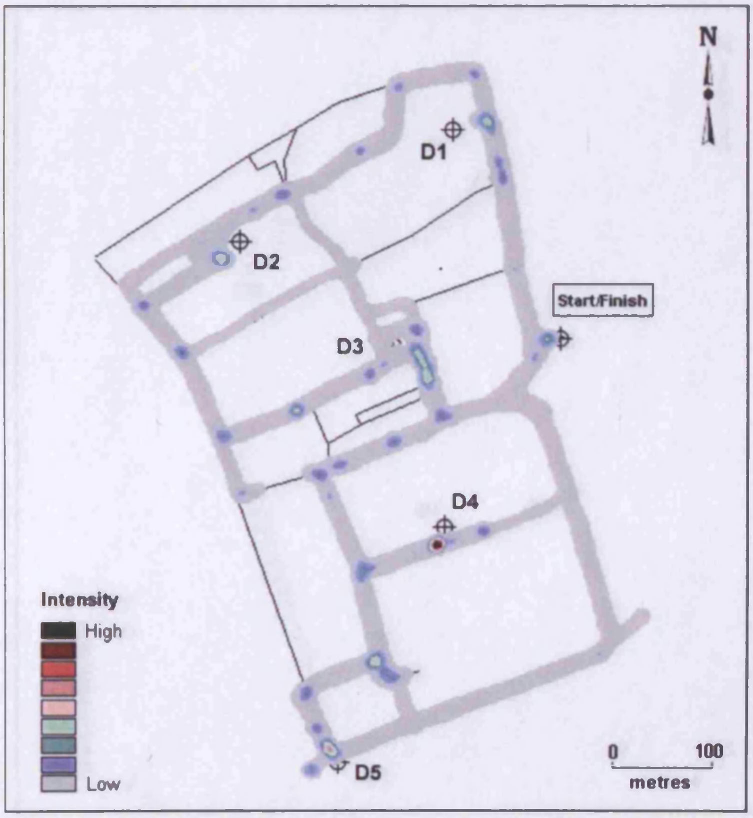


Figure 8.38 Boxplots of planning time ($T_{plan\text{-}total}$) for the four IN groups in settings U1 and U2

Eight intensity maps of the track position points recorded during wayfinding (Figure 8.39 to Figure 8.42) were also created for these four groups in both settings, in a similar way as described in the first case study above. The patterns shown in these intensity maps are discussed below to explore aspects of wayfinding behaviour of the four PDA information usage groups.

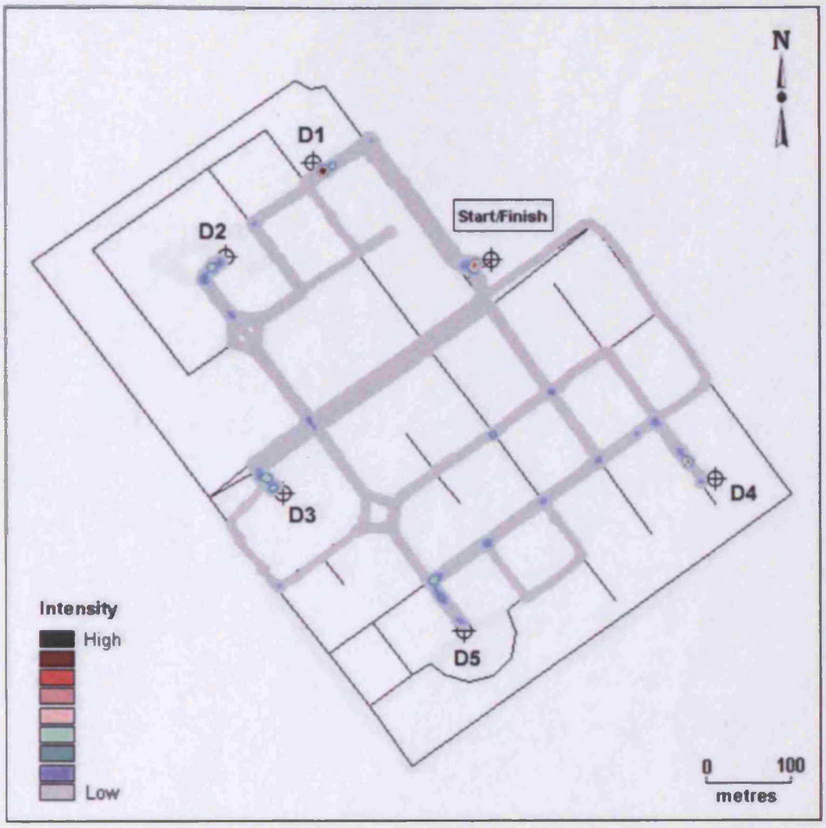


(a)

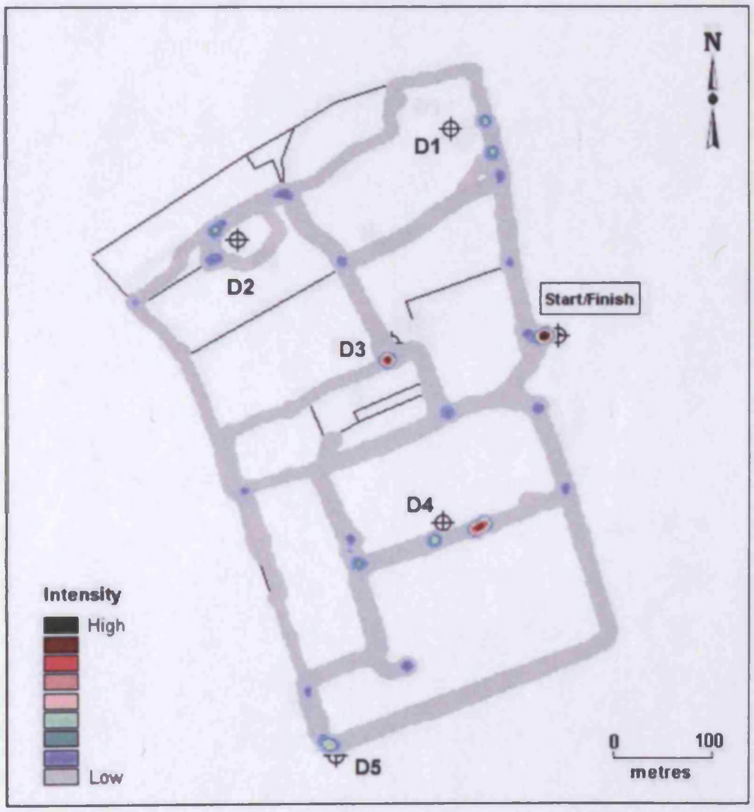


(b)

Figure 8.39 Intensity maps for PDA spatial information usage group IN-G1: (a) setting U1; (b) setting U2.

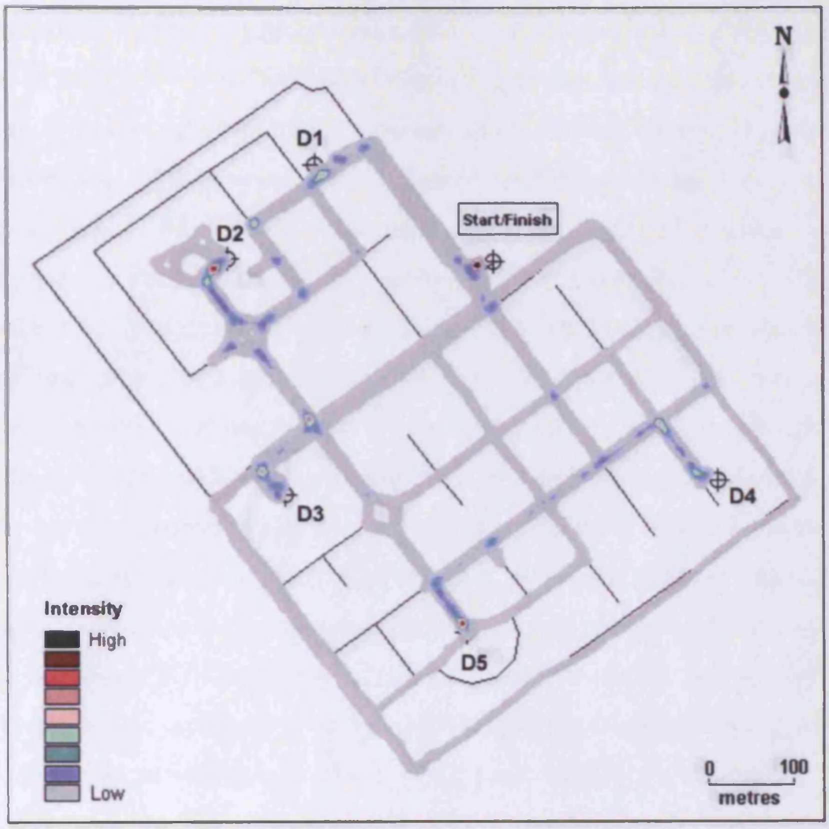


(a)

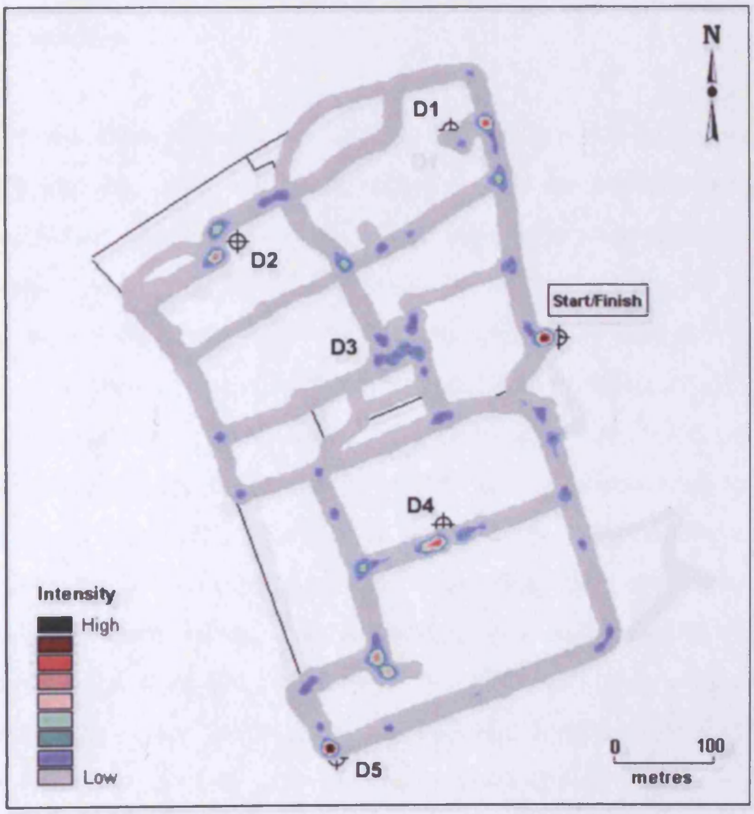


(b)

Figure 8.40 Intensity maps for PDA spatial information usage Group IN-G2:
(b) setting U1; (b) setting U2.



(a)



(b)

Figure 8.41 Intensity maps for PDA spatial information usage Group IN-G3:

(c) setting U1; (b) setting U2.

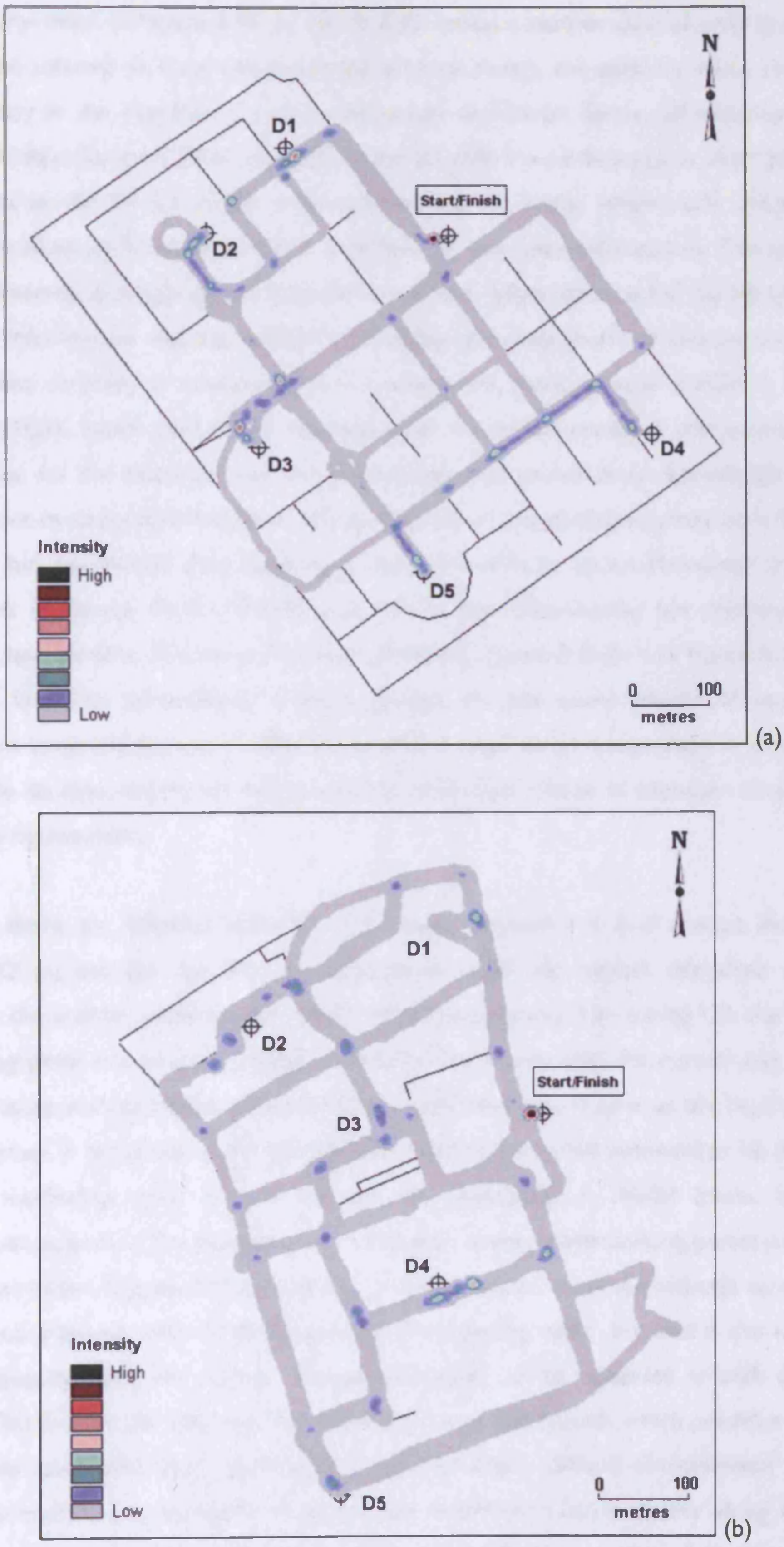


Figure 8.42 Intensity maps for PDA spatial information usage Group IN-G4:
(d) setting U1; (b) setting U2.

The intensity maps in Figure 8.39 to Figure 8.42 reveal a number of characteristics of these four groups relating to their wayfinding behaviours. Firstly, the patterns show that there is less diversity in the number of routes chosen by the IN-G1 Group of participants during their wayfinding (Figure 8.39(a) and (b)) compared with the participants in other groups. The participants in the IN-G1 Group have preferences for route information; therefore they were more likely to follow the routes described by the route information. This general lack of route diversity amongst the participants could also reflect that the knowledge gained from the route information was not sufficient to enable the participants to choose other routes. The greatest diversity in route choice is amongst the participants in IN-G3 in setting U1 (Figure 8.41(a)), which could have resulted from the mixed mode of information usage. It could either be the situation that the participants had gained more knowledge about the spatial layout by using different types of information, or the participants may have faced some difficulties but got around them by using a richer mix of information. Moreover, amongst the participants in Group IN-G2, IN-G3 and IN-G4, the difference in the diversity of route choices is less obvious in setting U2 (Figure 8.40 (b), Figure 8.41(b) and Figure 8.42(b)) than in setting U1. The participants in these groups all have some degree of map-oriented information usage although with different emphasis either in overview maps or detailed maps. It may also be that setting U2 offers a more restricted choice of rational routes between successive destinations.

Secondly, there are different patterns of hotspots between the four groups. As shown in Figure 8.42 (a) and (b), for IN-G4, the hotspots with the highest intensities are clearly located at the starting point for the whole wayfinding journey. For setting U2, the hotspot at the starting point has an even greater intensity. This implies that the participants with map-oriented usage with preference for overview maps spent more time at the beginning of the whole journey in familiarising themselves and studying the spatial information via the PDA to plan the wayfinding tasks. In contrast, for the participants in IN-G1 (route information oriented usage group), the hotspots are located at some of the starting points and most of the road junctions (Figure 8.39(a) and (b)). In other words, these participants tended not to spend much planning time at the beginning of wayfinding tasks, but access the information more frequently along the routes. This phenomenon can be observed in both settings U1 and U2. This may result from the nature of the route information which provides successive instructions along the route. Participants may well find it difficult to remember the whole route information, but are likely to access the information incrementally along the routes. However the participants in this group might need more information when they encounter challenging routes such as from D4 to D5 (in setting U2) along which is a cul-de-sac where many participants became lost or confused. For the participants in IN-G2 (Figure 8.40(a) and (b)), most of the hotspots are concentrated at the starting points of each wayfinding task. The intensity of such hotspots is noticeably higher at the starting points of each wayfinding task in U2, although this pattern of hotspots is similar in both settings. Such a pattern implies that the participants studied the spatial information more intensively in planning each coming wayfinding task. This is consistent with the results shown in Figure 8.38. The distributions of the hotpots in Figure 8.41(a) and (b) show that the concentration of hotspots are at the starting points and at locations having a more challenging spatial layout (e.g. the cul-de-sac on the route form D4 to D5 in setting U2, the roundabout on the route from D2 to D3 in setting U1).

The frequency of being lost or confused was also studied in relation to these PDA spatial information usage groups. For the four groups, a Kruskal-Wallis test shows that there is no significant difference with respect to these frequencies. This may be because of the small sample size in each group. Nevertheless, it can be seen from the boxplots (Figure 8.43) that the median frequency of being lost or confused is consistently higher in U2 amongst all groups compared with U1. The effect of setting appears to have had more influence on the participants in IN-G1 Group (Figure 8.43), with setting U2 having the greatest interquartile range in the frequency of being lost and confused.

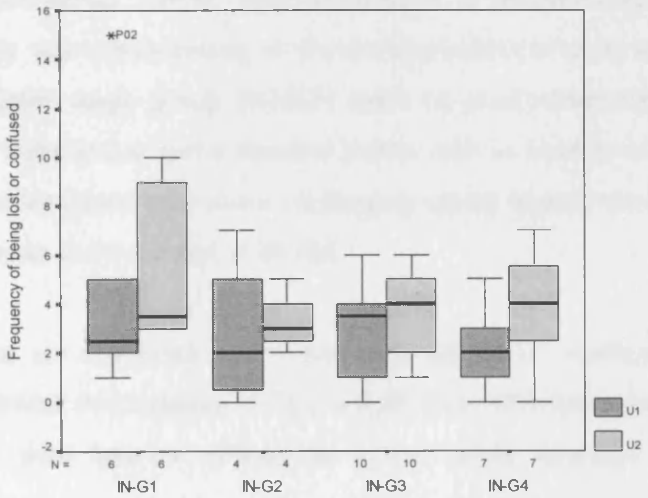


Fig 8.43 Frequency of being lost or confused for four IN groups in settings U1 and U2

Discussion: For the three spatial ability groups SA-G1 to SA-G3, the hotspots for SA-G3 are most concentrated at the starting point of the whole wayfinding journeys and early parts of the wayfinding tasks whilst the other two groups have a more even spread of high intensity locations at different start points for each task, road junctions and some more challenging locations. This phenomenon may reflect that the participants in SA-G3 (self-assessed high score in spatial ability) are more likely to familiarise themselves and study the spatial information from the PDA at the early stage of wayfinding and seem to benefit from developing their spatial knowledge of the layout at an early stage. Furthermore, the participants in SA-G3 seem to have exercised more diversity in their route choices which might have resulted from gaining good spatial knowledge at the beginning of the whole journey. The participants in SA-G1 are less likely to spend more time at the beginning of tasks for information but access information more frequently along the routes taken. For Group SA-G2, the participants appear to spend time studying the information for task planning and access information wherever difficulties occur. Moreover, the spatial layout does appear to have more of an influence on the wayfinding behaviour amongst the participants in SA-G1 and SA-G2.

For different PDA information usage groups, which represent the different preferences in using spatial information wayfinding, there are observable differences in the patterns of wayfinding. The participants with route information oriented usage (IN-G1) tend to take less time for studying the information in planning the task, but access information more intensively along the routes. In contrast, the participants with overview map oriented usage (IN-G4) spent more time studying information at the beginning of the whole journey and have gained more knowledge about the layout and acquire less information during the routes. Another map oriented group, IN-G2, with preferences in detailed maps also spent more time planning but this was concentrated at the starting points of each wayfinding task. The mixed mode information usage group (IN-G3) tends to need information at both starting points of wayfinding tasks and at some decision points such as road junctions. Furthermore, complex settings and locations with more challenging spatial layouts tend to have more an effect on the participants in IN-G1 and in IN-G3.

The planning time is an important and measurable aspect of wayfinding behaviour and information usage. Whilst the boxplots in Figure 8.38 show differences between groups, the intensity maps have shed light on differences in the spatial locations at which planning activities take place.

The group case studies have provided further insights into the relationships between different individuals, their wayfinding behaviours and the ways in which spatial information was acquired. The design of LBS wayfinding applications will thus need to consider individual spatial ability and information preferences. Furthermore there are implications as to where and in what situations more precise and detailed information will be required by these different groups.

8.7.2 Case studies: individual level

This part of the case study analysis focuses on individual participants selected from different self-assessed spatial ability groups (SA groups) and PDA spatial information usage groups (IN groups). The emphasis is on their strategies in using spatial information via the PDA during their wayfinding activities. To begin with, an overview of all 27 participants with their SA-grouping and IN-grouping is given in Table 8.28. In these case studies, there will be reference made to the number of times these participants were lost or confused, so also listed in Table 8.28 is the frequency with which participants were lost or confused during their wayfinding tasks in settings U1 and U2. For the aggregated 27 participants, Figure 8.44 shows that participants are more likely to be lost or confused in setting U2 than in setting U1, a Mann-Whitney U test: $U(27,27) = 248.5$ $p = 0.043$ confirming the significant difference. This again indicates that setting U2 is more challenging that U1.

PID	*SA-group*	*IN-group*	Setting U1	Setting U2
P02	3	1	15	10
P03	3	4	2	3
P04	3	2	3	3
P05	1	1	2	3
P06	1	4	0	0
P07	2	2	1	2
P08	1	4	1	5
P09	3	3	2	2
P11	3	2	7	3
P12	3	4	2	2
P13	2	3	5	6
P14	3	4	5	7
P15	3	3	1	2
P16	2	1	5	3
P17	1	1	2	9
P18	1	3	0	5
P19	1	4	1	6
P20	3	3	4	1
P21	2	3	4	5
P22	1	1	1	4
P23	2	3	6	4
P24	3	3	1	5
P25	2	3	3	4
P26	3	2	0	5
P27	2	3	4	4
P29	3	1	3	3
P30	3	4	4	4

Table 8.28 Frequency of being lost and confused for all participants in both settings

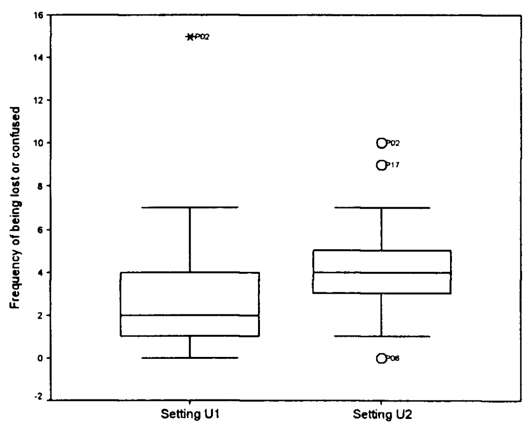


Figure 8.44 Boxplot of the frequency in both settings

For the eight participants selected for this Section, there are two participants in each of the four IN groups. The two participants in each of four IN groups are not from the same SA groups. All SA groups are represented. Listed in Table 8.29 are the eight participants with a number of variables describing their wayfinding characteristics. The variables shown in the table are: participant id (PID); self-assessed spatial ability group (SA group); PDA spatial information group (IN group); frequency of being lost or confused (*Lost/Confused*); the total distance travelled for the wayfinding tasks ($D_{travelled\text{-}total}$); the time taken for completing the wayfinding tasks ($T_{completion\text{-}total}$); frequency of PDA information access ($F_{pda\text{-}total}$); the time spent using the information from the PDA ($T_{pda\text{-}total}$); the time used for task planning ($T_{plan\text{-}total}$).

PID	SA-Group	IN-Group	Lost/Confused		$D_{travelled\text{-}total}$		$T_{completion\text{-}total}$		$F_{pda\text{-}total}$		$T_{pda\text{-}total}$		$T_{plan\text{-}total}$	
			U1	U2	U1	U2	U1	U2	U1	U2	U1	U2	U1	U2
P05	1	1	2	3	2840.7	2563.3	1319	2548	37	125	197	1161	174	601
P07	2	2	1	2	3268.5	2261.8	1614	1888	48	55	428	808	429	853
P11	3	2	7	3	3535.7	2590.2	2083	1578	73	64	598	523	353	350
P19	1	4	1	6	2966.4	2618.7	1366	1605	43	63	341	473	197	245
P20	3	3	4	1	3780.2	2419.4	1636	1356	25	33	268	330	223	360
P27	2	3	4	4	3242.1	2596.5	1817	1898	63	57	394	497	235	292
P29	3	1	3	3	3161.4	2689.8	1612	1467	41	37	477	467	321	169
P30	3	4	4	4	3109.6	2340.8	1254	1384	54	78	149	409	78	264

Table 8.29 Eight participants studied at the individual level (shaded figures are above median values for all 27 participants).

An information usage track map was created for each of these participants based on the integrated PDA information usage data set with wayfinding position points. The type of spatial information accessed and the location where the PDA was consulted are mapped along the route taken during wayfinding activities. Thus a total of 16 information usage track maps were created for the 8 participants, one for each of the two settings. These are shown in Figures 8.45 to 8.52. Also illustrated in Figures 8.45 to 8.52 are the sketch maps that the participants drew as a part of the post-experiment questionnaires immediately after each set of wayfinding tasks. Each of these sketch maps is displayed under the corresponding wayfinding track completed by that participant. To recap a design element of the experiments (§ 6.4), the last task in each setting (the return from D5 back to the car park from whence they had started) had no route assistance available through the PDA. This was to ensure that all participants were only able to access map information for this final task. To recap: 'route information' refers to the information which provides procedural information such as a route description; 'overview map' refers to the general layout map of the area with landmarks/road names which can be shown by clicking on the map; and 'detailed map' refers to zoomed in maps showing a restricted part of the area but can be scrolled and resembles traditional paper maps in its content and symbology.

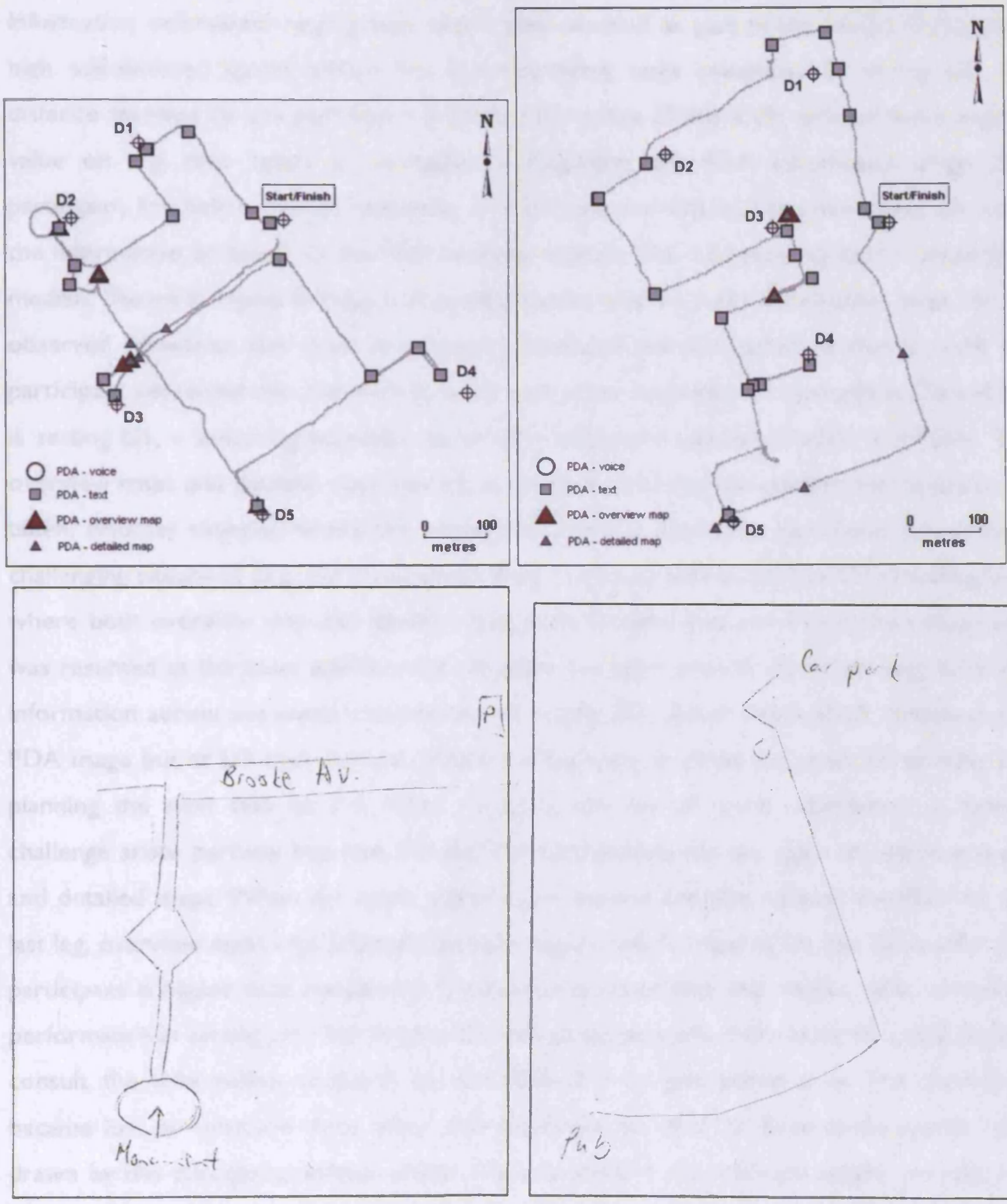


Figure 8.45 Participant P29 (IN-G1, SA-G3): (a) information track map – setting U1; (b) information track map – setting U2; (c) sketch map – setting U1; (d) sketch map – setting U2.

Participant P29. This participant (Figure 8.45) is from Group IN-G1, which is the route information orientated usage group, and is also classified as part of the SA-G3 Group with high self-assessed spatial ability. For the wayfinding tasks completed in setting U1, the distance traveled by this participant is below the median (Table 8.29) with an above median value on the time taken for completion. Regarding the PDA information usage, this participant has below median frequency of information access, but the time spent for using the information accessed via the PDA is above median. The total planning time is also above median. Shown in Figure 8.45(a), a noticeable preference for route information usage can be observed. However, this route dominated information pattern started to change when the participant perceived that the coming tasks were more complex. For example at D2 and D3 is setting U1, a switching between route information and map information is evident. The overview maps and detailed maps were both used to assist in understanding the routes to be taken. Another situation where this strategy was used is where the participant encountered challenging situations (e.g. the roundabout along the route between D2 to D3 in setting U1), where both overview map and detailed map were brought into use. The route information was resumed as the main source once the maps had been used. A similar strategy in spatial information access and usage is observable in setting U2. Route information dominates the PDA usage but at D3 overview and detailed maps were accessed and used for assisting the planning the next task to D4. After resuming the use of route information, a further challenge arose partway between D3 and D4 necessitating the use again of overview maps and detailed maps. When the route information was not available through the PDA on the last leg, overview maps and detailed map were again used. For setting U2, the $T_{pda\text{-}total}$ for this participant is higher than median but the $F_{pda\text{-}total}$ is lower than the median value, mirroring performance in setting U1. This implies that the participant was more likely to spend time to consult the information accessed on the PDA than to just glance at it. The participant became lost or confused three times each in settings U1 and U2. Both of the sketch maps drawn by this participant exhibit similar characteristics in that they are simple and only the last leg of the journey was recorded. The sketch map for U1 has the main landmarks whilst sketch map for U2 has the correct orientation but only the starting point and destination shown. This might reflect the fact that this individual had low comprehension of the whole spatial layout of the setting, but had nevertheless developed a degree of spatial knowledge with help from the PDA sufficient for the wayfinding tasks.

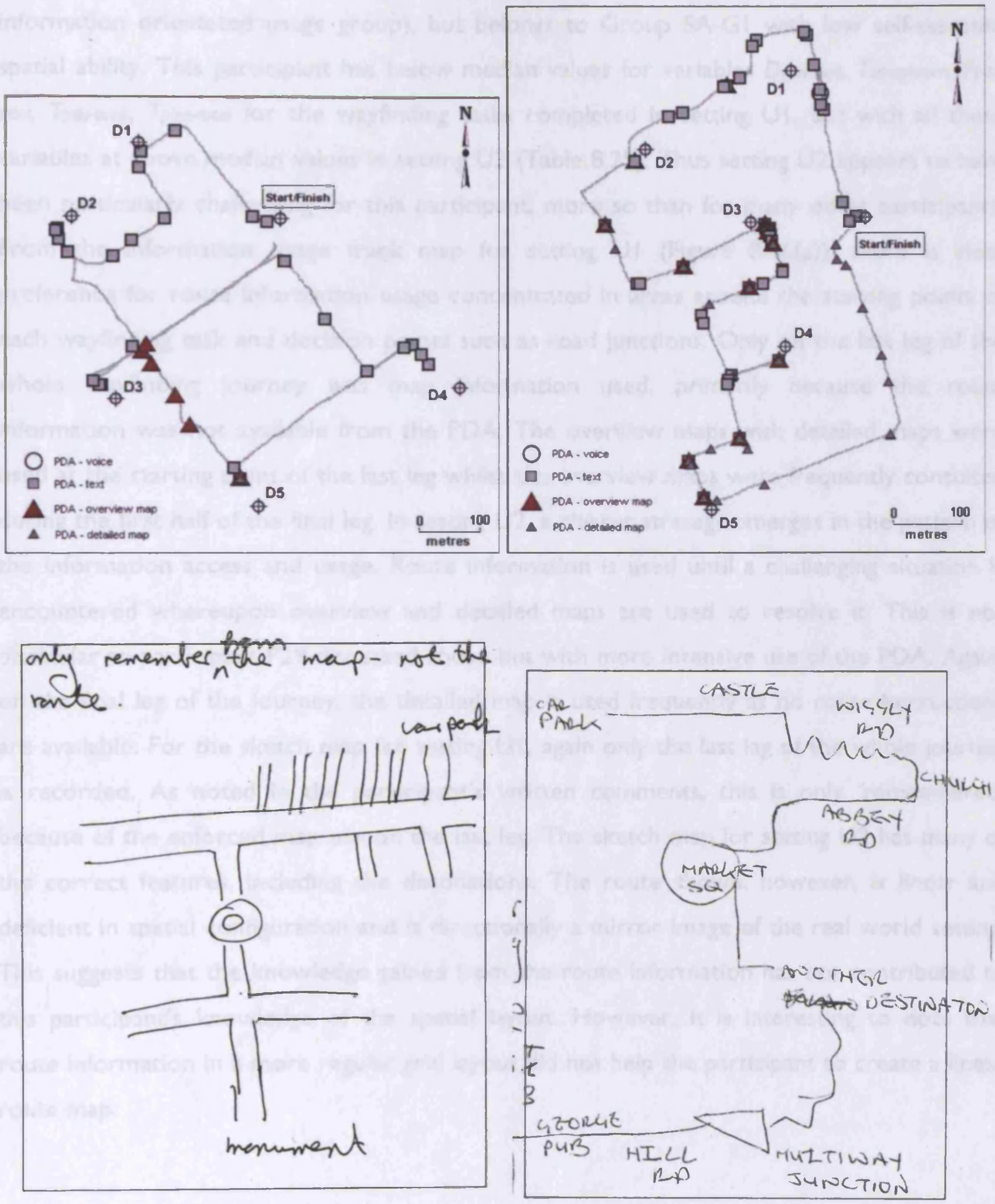


Figure 8.46 Participant P05 (IN-G1, SA-G1): (a) information track map – setting U1; (b) information track map – setting U2; (c) sketch map – setting U1; (d) sketch map – setting U2.

Participant P05. This participant (Figure 8.46) is also from the IN-G1 Group (route information orientated usage group), but belongs to Group SA-G1 with low self-assessed spatial ability. This participant has below median values for variables $D_{travelled}$, $T_{completion}$, $F_{pda-total}$, $T_{pda-total}$, $T_{plan-total}$ for the wayfinding tasks completed in setting U1, but with all these variables at above median values in setting U2 (Table 8.29). Thus setting U2 appears to have been particularly challenging for this participant, more so than for many other participants. From the information usage track map for setting U1 (Figure 8.46(a)), there is clear preference for route information usage concentrated in areas around the starting points of each wayfinding task and decision points such as road junctions. Only on the last leg of the whole wayfinding journey was map information used, primarily because the route information was not available from the PDA. The overview maps with detailed maps were used at the starting point of the last leg whilst the overview maps were frequently consulted during the first half of the final leg. In setting U2, a clearer strategy emerges in the pattern of the information access and usage. Route information is used until a challenging situation is encountered whereupon overview and detailed maps are used to resolve it. This is not dissimilar to participant P29 discussed above but with more intensive use of the PDA. Again, on the final leg of the journey, the detailed map is used frequently as no route instructions are available. For the sketch map for setting U1, again only the last lag of the whole journey is recorded. As noted in the participant's written comments, this is only 'remembered' because of the enforced map use on the last leg. The sketch map for setting U2 has many of the correct features, including the destinations. The route shown, however, is linear and deficient in spatial configuration and is directionally a mirror image of the real world setting. This suggests that the knowledge gained from the route information has not contributed to this participant's knowledge of the spatial layout. However, it is interesting to note that route information in a more regular grid layout did not help the participant to create a linear route map.

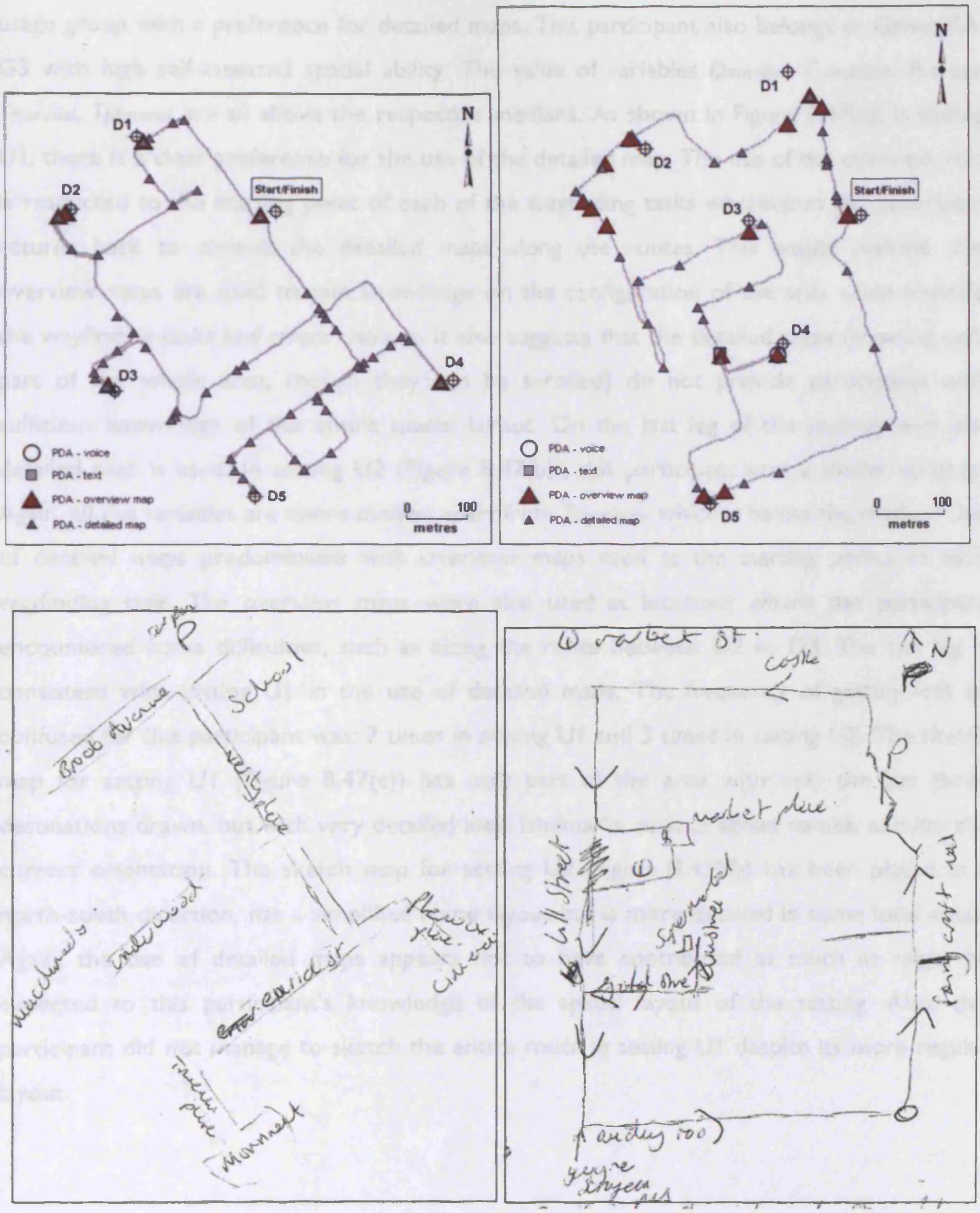


Figure 47 Participant P11 (IN-G2, SA-G3): (a) information track map – setting U1; (b) information track map – setting U2; (c) sketch map – setting U1; (d) sketch map – setting U2.

Participant P11. This participant (Figure 8.47) is from Group IN-G2, which is map oriented usage group with a preference for detailed maps. This participant also belongs to Group SA-G3 with high self-assessed spatial ability. The value of variables $D_{travelled}$, $T_{completion}$, $F_{pda-total}$, $T_{pda-total}$, $T_{plan-total}$ are all above the respective medians. As shown in Figure 8.47(a), in setting U1, there is a clear preference for the use of the detailed map. The use of the overview map is restricted to the starting point of each of the wayfinding tasks whereupon this participant returns back to consult the detailed maps along the routes. This would indicate that overview maps are used to gain knowledge on the configuration of the area when planning the wayfinding tasks and route choices. It also suggests that the detailed maps (showing only part of the whole area, though they can be scrolled) do not provide participants with sufficient knowledge of the entire spatial layout. On the last leg of the journey only the detailed map is used. In setting U2 (Figure 8.47(b)), this participant uses a similar strategy. Again, all the variables are above median apart from $T_{completion}$ which is below the median. Use of detailed maps predominates with overview maps used at the starting points of each wayfinding task. The overview maps were also used at locations where this participant encountered some difficulties, such as along the route between D2 to D3. The last leg is consistent with setting U1 in the use of detailed maps. The frequency of getting lost or confused for this participant was: 7 times in setting U1 and 3 times in setting U2. The sketch map for setting U1 (Figure 8.47(c)) has only part of the area with only the last three destinations drawn, but with very detailed local landmarks such as street names, and has the correct orientation. The sketch map for setting U2 (Figure 8.47(d)) has been placed in a north-south direction, has a simplified route layout but is more detailed in some local areas. Again, the use of detailed maps appears not to have contributed as much as might be expected to this participant's knowledge of the spatial layout of the setting. Also, this participant did not manage to sketch the entire route in setting U1 despite its more regular layout.

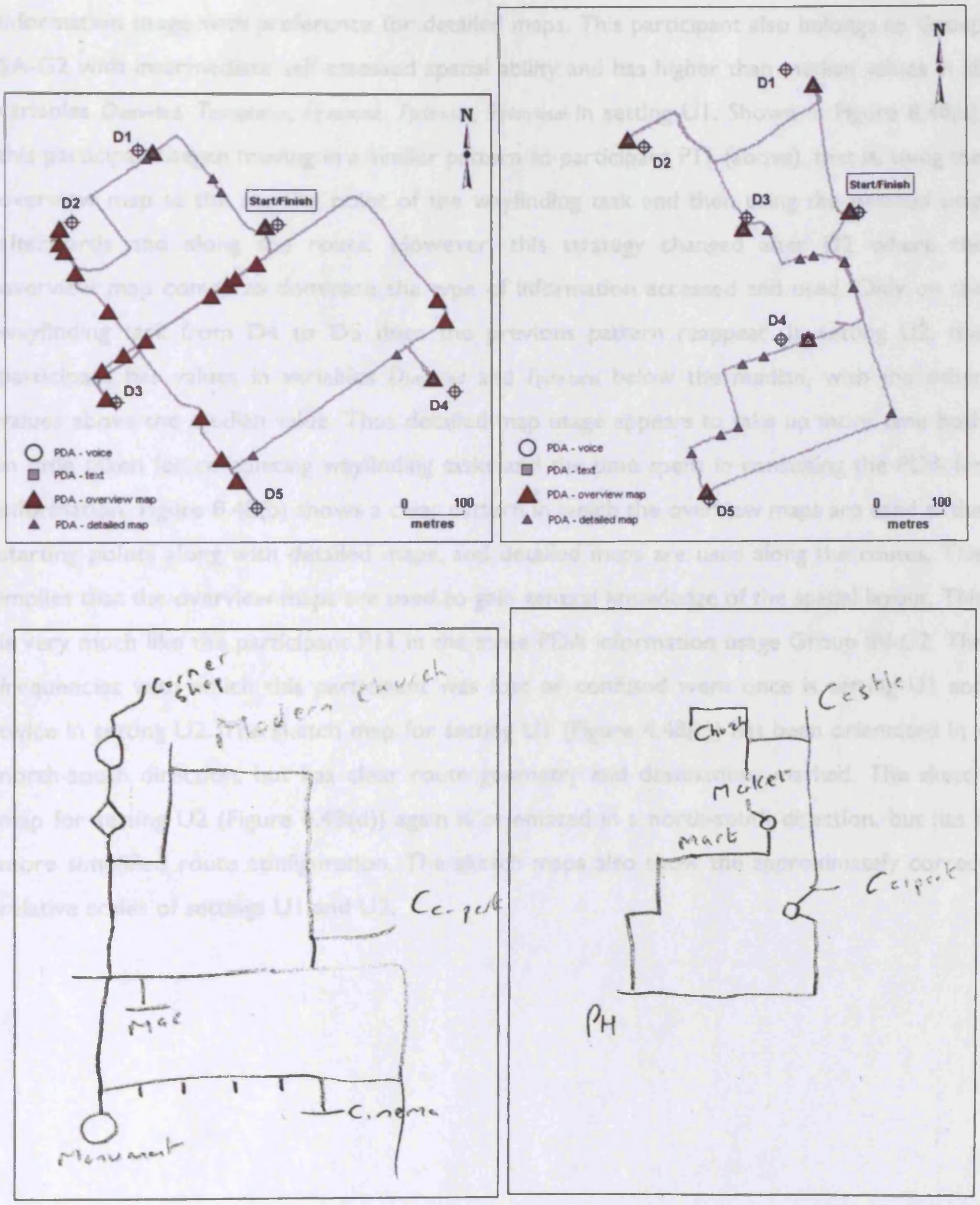


Figure 48 Participant P07 (IN-G2, SA-G2): (a) information track map – setting U1; (b) information track map – setting U2; (c) sketch map – setting U1; (d) sketch map – setting U2.

Participant P07. This participant (Figure 8.48) is also from Group IN-G2, map oriented information usage with preference for detailed maps. This participant also belongs to Group SA-G2 with intermediate self-assessed spatial ability and has higher than median values in all variables $D_{travelled}$, $T_{completion}$, $F_{pda\text{-}total}$, $T_{pda\text{-}total}$, $T_{plan\text{-}total}$ in setting U1. Shown in Figure 8.48(a), this participant began moving in a similar pattern to participant P11 (above), that is, using the overview map at the starting point of the wayfinding task and then using the detailed map afterwards and along the route. However, this strategy changed after D2 where the overview map comes to dominate the type of information accessed and used. Only on the wayfinding task from D4 to D5 does the previous pattern reappear. In setting U2, this participant has values in variables $D_{travelled}$ and $F_{pda\text{-}total}$ below the median, with the other values above the median value. Thus detailed map usage appears to take up more time both in time taken for completing wayfinding tasks and the time spent in consulting the PDA for information. Figure 8.48(b) shows a clear pattern in which the overview maps are used at the starting points along with detailed maps, and detailed maps are used along the routes. This implies that the overview maps are used to gain general knowledge of the spatial layout. This is very much like the participant P11 in the same PDA information usage Group IN-G2. The frequencies with which this participant was lost or confused were once is setting U1 and twice in setting U2. The sketch map for setting U1 (Figure 4.48(c)) has been orientated in a north-south direction, but has clear route geometry and destinations marked. The sketch map for setting U2 (Figure 4.48(d)) again is orientated in a north-south direction, but has a more simplified route configuration. The sketch maps also show the approximately correct relative scales of settings U1 and U2.

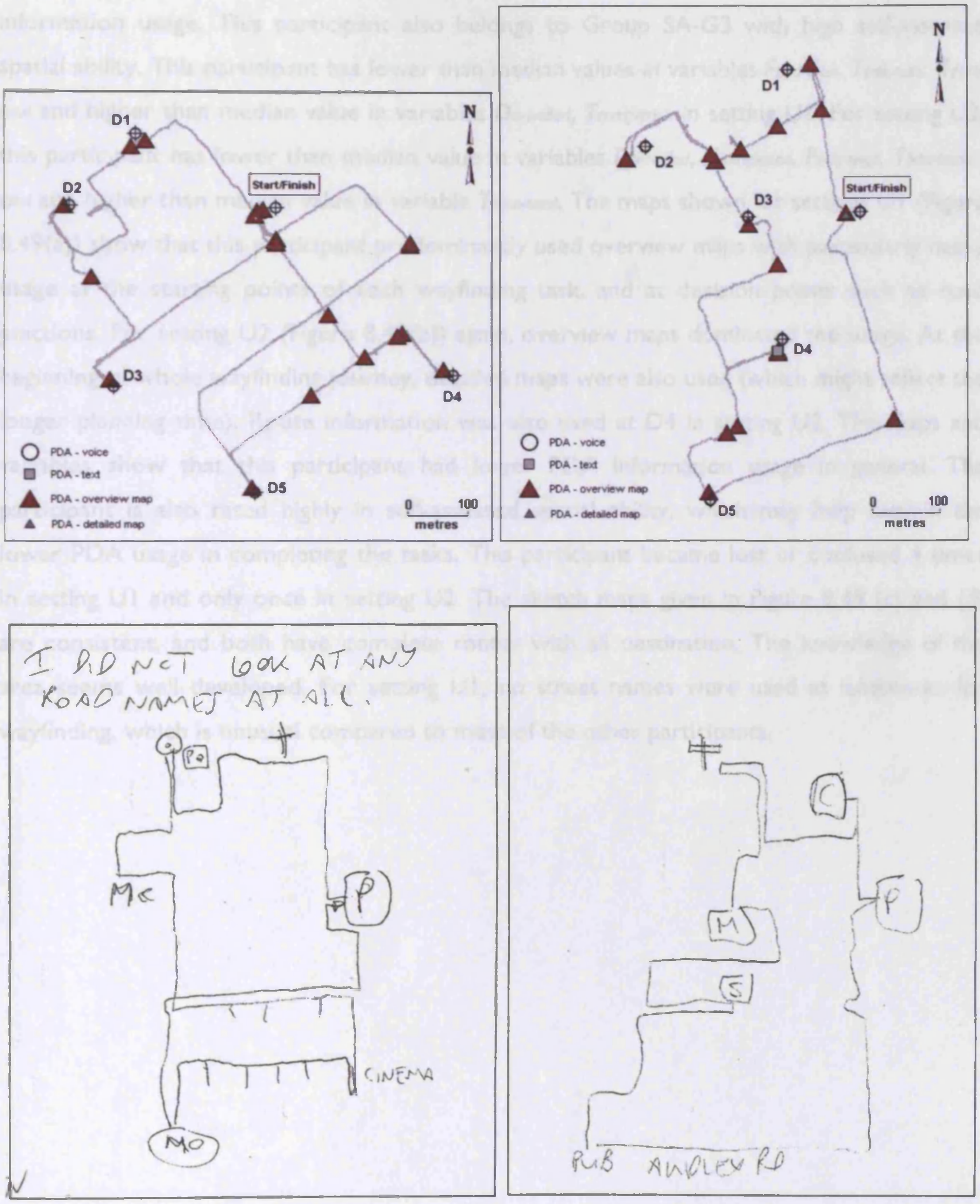


Figure 49 Participant P20 (IN-G3, SA-G3): (a) information track map – setting U1; (b) information track map – setting U2; (c) sketch map – setting U1; (d) sketch map – setting U2.

Participant P20. This participant (Figure 8.49) is from Group IN-G3, which is mix mode of information usage. This participant also belongs to Group SA-G3 with high self-assessed spatial ability. This participant has lower than median values in variables $F_{pda\text{-}total}$, $T_{pda\text{-}total}$, $T_{plan\text{-}total}$ and higher than median value in variables $D_{travelled}$, $T_{completion}$ in setting U1. For setting U2, this participant has lower than median value in variables $D_{travelled}$, $T_{completion}$, $F_{pda\text{-}total}$, $T_{pda\text{-}total}$, -total and higher than median value in variable $T_{plan\text{-}total}$. The maps shown for settings U1 (Figure 8.49(a)) show that this participant predominantly used overview maps with particularly heavy usage at the starting points of each wayfinding task, and at decision points such as road junctions. For setting U2 (Figure 8.49(b)) again, overview maps dominated the usage. At the beginning of whole wayfinding journey, detailed maps were also used (which might reflect the longer planning time). Route information was also used at D4 in setting U2. The maps and variables show that this participant had lower PDA information usage in general. The participant is also rated highly in self-assessed spatial ability, which may help explain the lower PDA usage in completing the tasks. This participant became lost or confused 4 times in setting U1 and only once in setting U2. The sketch maps given in Figure 8.49 (c) and (d) are consistent, and both have complete routes with all destination. The knowledge of the area seems well developed. For setting U1, no street names were used as landmarks for wayfinding, which is unusual compared to most of the other participants.

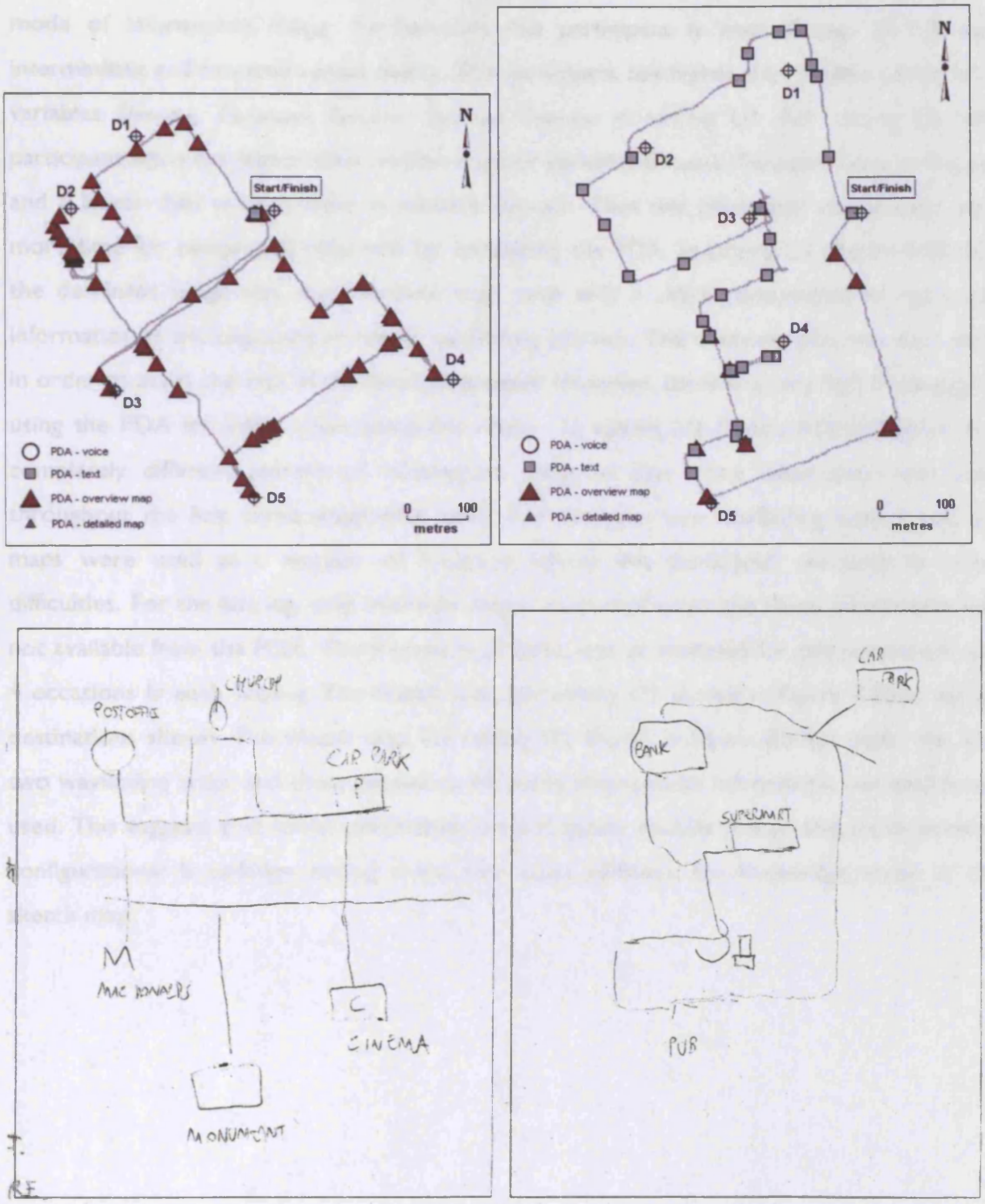


Figure 50 Participant P27 (IN-G3, SA-G2): (a) information track map – setting U1; (b) information track map – setting U2; (c) sketch map – setting U1; (d) sketch map – setting U2.

Participant P27. This participant (Figure 8.50) is also from IN- G3 Group, which is mixed mode of information usage. Furthermore this participant is from Group SA-G2 with intermediate self-assessed spatial ability. This participant has higher than median values in all variables $D_{travelled}$, $T_{completion}$, $F_{pda\text{-}total}$, $T_{pda\text{-}total}$, $T_{plan\text{-}total}$ in setting U1. For setting U2, this participant again has higher than median value in variables $D_{travelled}$, $T_{completion}$, $F_{pda\text{-}total}$, $T_{pda\text{-}total}$ and a lower than median value in variable $T_{plan\text{-}total}$. Thus this participant consistently used more time for completing tasks and for consulting the PDA. In setting U1 (Figure 8.50 (a)), the dominant usage was the overview map, with only a single consultation of the route information at the beginning of whole wayfinding journey. The overview map was then used in order to assist the rest of the wayfinding tasks. However, there is a very high frequency in using the PDA for information along the route. In setting U2 (Figure 8.50(b)), there is a completely different pattern of information usage in that route information was used throughout the first three wayfinding tasks. For the next two wayfinding tasks, overview maps were used at a number of locations where this participant encountered some difficulties. For the last leg, only overview maps were used when the route information was not available from the PDA. The frequency of being lost or confused for this participant was 4 occasions in each setting. The sketch map for setting U1 shown in Figure 8.50(a) has all destinations shown. The sketch map for setting U2 shown in Figure 8.50(b) omits the first two wayfinding tasks, and these happen to be those where route information was exclusively used. This suggests that route information did not appear to help this participant to develop configurational knowledge during these two tasks sufficient for knowledge recall in the sketch map.

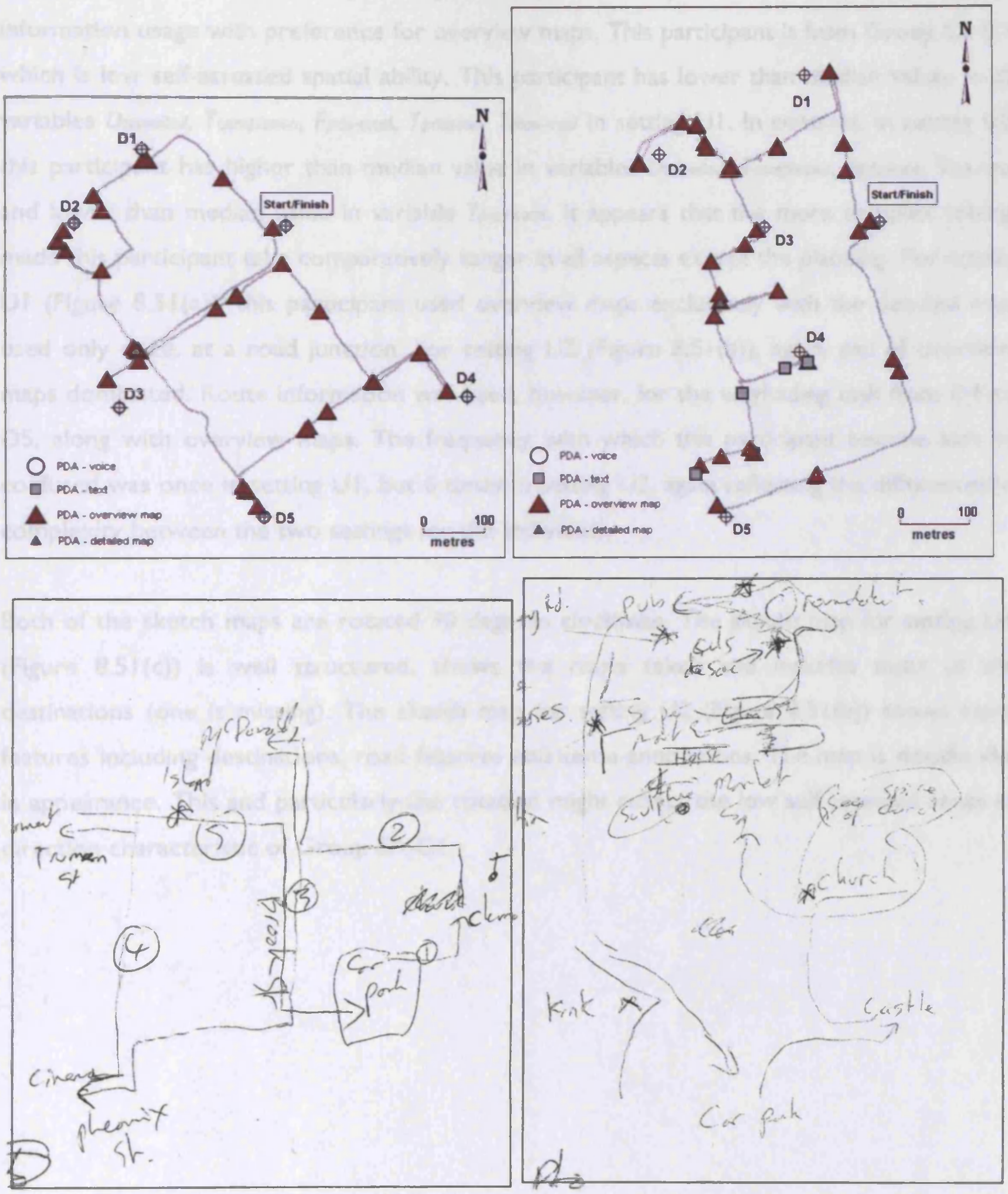


Figure 51 Participant P19 (IN-G4, SA-G1): (a) information track map – setting U1; (b) information track map – setting U2; (c) sketch map – setting U1; (d) sketch map – setting U2.

Participant P19. This participant (Figure 8.51) is in Group IN-G4 which is map oriented information usage with preference for overview maps. This participant is from Group SA-G1 which is low self-assessed spatial ability. This participant has lower than median values in all variables $D_{travelled}$, $T_{completion}$, $F_{pda\text{-}total}$, $T_{pdatotal}$, $T_{plan\text{-}total}$ in setting U1. In contrast, in setting U2 this participant has higher than median value in variables $D_{travelled}$, $T_{completion}$, $F_{pda\text{-}total}$, $T_{pda\text{-}total}$ and lower than median value in variable $T_{plan\text{-}total}$. It appears that the more complex setting made this participant take comparatively longer in all aspects except the planning. For setting U1 (Figure 8.51(a)), this participant used overview maps exclusively with the detailed map used only once, at a road junction. For setting U2 (Figure 8.51(b)), again, use of overview maps dominated. Route information was used, however, for the wayfinding task from D4 to D5, along with overview maps. The frequency with which this participant became lost or confused was once in setting U1, but 6 times in setting U2, again reflecting the differences in complexity between the two settings for this individual.

Both of the sketch maps are rotated 90 degrees clockwise. The sketch map for setting U1 (Figure 8.51(c)) is well structured, shows the route taken and includes most of the destinations (one is missing). The sketch map for setting U2 (Figure 8.51(b)) shows many features including destinations, road features and some annotations. The map is doodle-like in appearance. This and particularly the rotation might reflect the low self-assessed sense of direction characteristic of Group SA-G1.

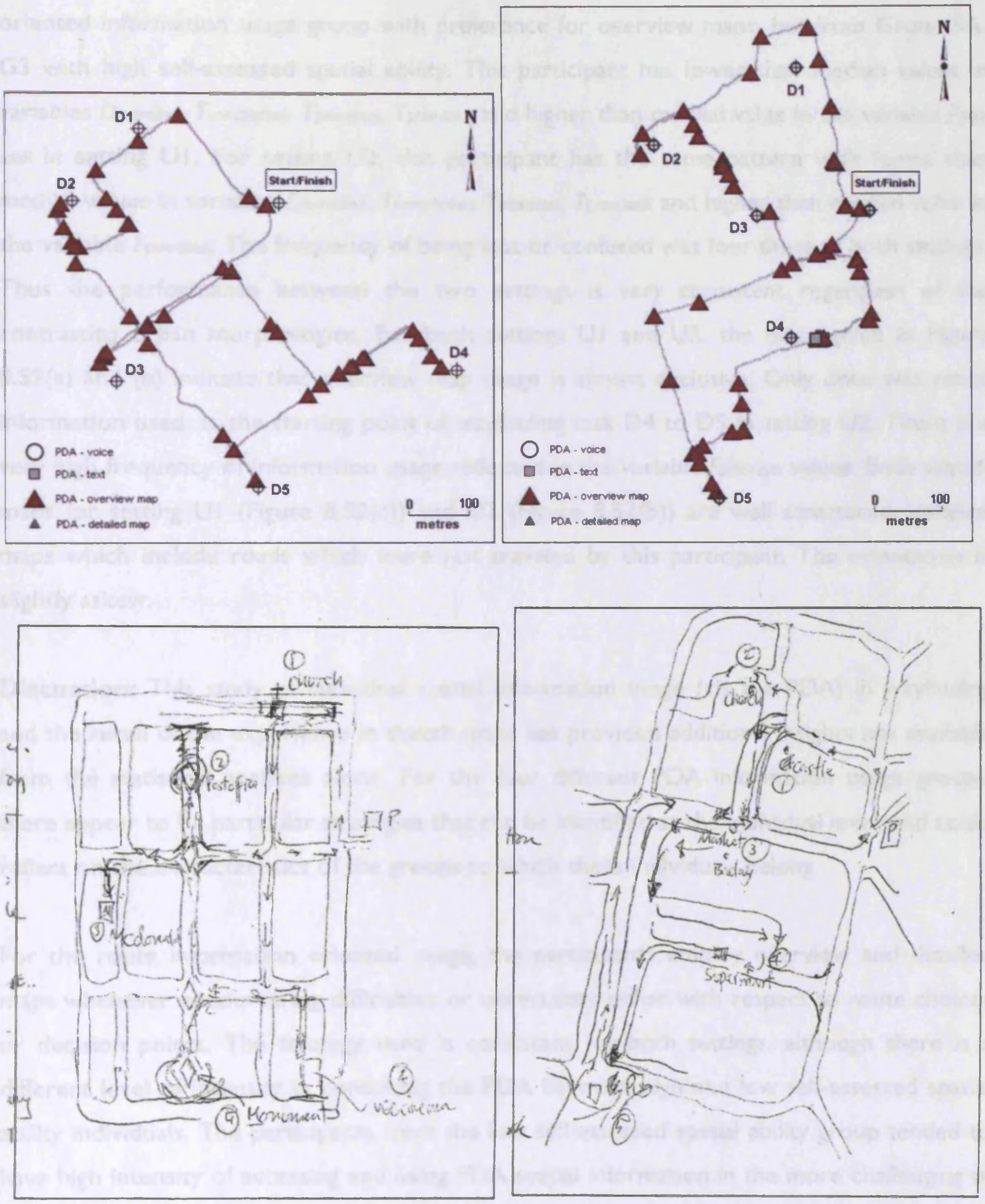


Figure 52 Participant P30 (IN-G4, SA-G3): (a) information track map – setting U1; (b) information track map – setting U2; (c) sketch map – setting U1; (d) sketch map – setting U2.

Participant P30. This participant (Figure 8.52) is also from Group IN-G4, which is map oriented information usage group with preference for overview maps, but from Group SA-G3 with high self-assessed spatial ability. This participant has lower than median values in variables $D_{travelled}$, $T_{completion}$, $T_{pda\text{-}total}$, $T_{plan\text{-}total}$ and higher than median value in the variable $F_{pda\text{-}total}$ in setting U1. For setting U2, this participant has the same pattern with lower than median values in variables $D_{travelled}$, $T_{completion}$, $T_{pda\text{-}total}$, $T_{plan\text{-}total}$ and higher than median value in the variable $F_{pda\text{-}total}$. The frequency of being lost or confused was four times in both settings. Thus the performance between the two settings is very consistent regardless of the contrasting urban morphologies. For both settings U1 and U2, the maps given in Figure 8.52(a) and (b) indicate that overview map usage is almost exclusive. Only once was route information used: at the starting point of wayfinding task D4 to D5 in setting U2. There is a very high frequency of information usage reflected in the variable $F_{pda\text{-}total}$ values. Both sketch maps for setting U1 (Figure 8.52(c)) and U2 (Figure 8.52(b)) are well structured, detailed maps which include roads which were not traveled by this participant. The orientation is slightly askew.

Discussion: This study of individual spatial information usage (via the PDA) in wayfinding and the recall of the experience in sketch maps has provided additional insights not available from the statistical analyses alone. For the four different PDA information usage groups, there appear to be particular strategies that can be identified at the individual level, and could reflect on the characteristics of the groups to which these individuals belong.

For the route information oriented usage, the participants employ overview and detailed maps whenever encountering difficulties or uncertainty either with respect to route choices or decision points. The strategy used is consistent for both settings, although there is a different level of intensity in consulting the PDA between high and low self-assessed spatial ability individuals. The participants from the low self-assessed spatial ability group tended to have high intensity of accessing and using PDA spatial information in the more challenging of the settings (U2). The knowledge of the areas does not appear to include comprehension of their spatial configurations, although this is sufficient for completing the wayfinding tasks.

For the detailed map oriented usage, there is a pattern of using overview maps for planning wayfinding tasks and route choices. The case studies developed here also indicated that these participants do not appear to develop knowledge of the whole area configuration from the information from detailed maps in which the area can only partially be viewed. Again, the difference in spatial ability group does not appear to have the main effect on the strategies of information usages. Moreover, the strategy used is generally consistent between both settings.

For the mixed mode of information usage, there is an alternation in using different types of information amongst the two different settings. It appears that participants choose whatever suites their purpose for the particular environment. This implies that the different settings have an influence on the types of information used for the wayfinding tasks.

For the overview map oriented information usage, the overview maps are used dominantly, with only very few other types of information used occasionally. Again there is consistency in the usage strategy between the two settings and between the two individuals from the different self-assessed spatial ability groups. However, differences arise between the two self-assessed spatial ability groups represented here in respect of the knowledge developed of the areas. This analysis of the individual level strategies is consistent with the group level studies in the previous Section.

CHAPTER NINE
Conclusions and Future Research

As a fundamental spatial activity in people's daily lives, wayfinding is an interactive behaviour between people and their environments. The acquisition of spatial knowledge and performance of spatial tasks such as wayfinding involves interactions between people and their environments. Interaction between humans and the environment has been researched from cognitive aspects over the decades and various conceptual models or schema have been established to understand how people structure and develop an inner representation through recording and processing information based on their perception of the real-world and inferences about it. There has been rather less focus upon studying overt behaviour during the actual process of wayfinding (Chapter 3). On the other hand, the rapid development of wireless mobile information and communication technologies is providing new ways to deliver spatial information to the individual on the move. Thus there is every possibility for spatial information to be acquired by individuals using their wireless mobile devices in real-time, at any location. Much of this information could be used to assist wayfinding, be interactive and have the content dynamically refreshed with updates. These developments are pertinent to the study of people's spatial abilities, and the ways in which they acquire spatial information and develop spatial knowledge. Yet to date, the role of new technologies has not been assimilated into wayfinding research. This thesis has highlighted the implications and articulates the questions and challenges arising from the impacts of NICTs (Chapter 2) for wayfinding and spatial information research. It seems axiomatic that these new ways of accessing spatial information are affecting the nature of human wayfinding, but as yet we understand rather little about these developments.

In this research, urban wayfinding has been studied from a new perspective. The technological element has been included into the wayfinding research, both as a new aspect of interaction between people and a source of spatial information, and as mediation between people and the environment. Wireless mobile devices as sources of spatial information have a pivotal role. Thus by studying the details of these interactions and spatial information transactions, we can gain an understanding and insight into the level of information that is sufficient to individual needs, the desired types of information, frequency of use and preferred modes of communication for completing wayfinding tasks. This understanding can be set within the context of an individual's spatial ability. Moreover, the actions taken in response to the knowledge gained from the acquired spatial information can also be studied in relation to the different spatial configurations of the environment.

To restate the aim of this research: it has been to investigate the real-time interactions and information transactions between individuals, their mobile devices and urban environments during pedestrian wayfinding activities.

In this research, a dynamic interaction model (Chapter 5) has been devised at a conceptual level with an explicit focus on the overt interactions and spatial information transactions between individuals, mobile devices and urban environments. This conceptual model provides the framework for the research within which many aspects of the interactions, spatial information acquisition, and individual wayfinding behaviour can be studied. The conceptual model differs from many existing human-environment interaction models because the technological element, in the form of wireless mobile devices, has been brought into the interaction between people and their environments. Furthermore, the mobile device is considered as an information source with which individuals actively interact during spatial wayfinding tasks.

In order to implement aspects of the conceptual model, a novel methodological approach (Chapter 5) has been developed with the focus on collecting and analysing data from real-time spatial information transactions and overt interaction behaviour during spatial activities such as wayfinding. The approach consisted of experiments in a VR-based test environment, combined with questionnaires and debriefing interviews. This approach provided the means to collect a rich data set regarding individuals, their spatial information transactions and usage, overt spatial behaviour and interactions with the environment. It could be used to overcome many of the challenges faced in studying the actual process in real-time, whilst avoiding the shortcomings that result when such measurements are carried out after the wayfinding activities have ceased. Furthermore, this approach could be deployed in the study of needs and uses of spatial information in mobile situations with the emphasis on the individual user.

For this research, a VR-based test environment has been designed and created. It provides realistic stable urban settings in which individuals can 'walk' and access spatial information using their mobile devices in order to complete wayfinding tasks. During these tasks users can interact with the mobile device to obtain different types of spatial information, and at the same time the details of these transactions can be observed and recorded. The test environment comprises of three main parts: two contrasting VR urban models with their own distinctive layouts and mix of architectures, a mobile device (a PDA) providing simulated LBS applications and multi-source data collection software for recording individual behaviour and interactions with the mobile device. Such a test environment could also be deployed for a wide range of investigations in the design and use of LBS applications, and other mobile technologies, with a user focus.

The validity of wayfinding experiments in the VR-based test environments has been assured from three aspects. Firstly, the commonality of wayfinding strategies and features used by the participants in the VR test environment and in the real-world was confirmed through the two consistent sets of feedback following wayfinding experiments in two different urban settings. The results show that all participants reported that they used a similar approach and features in the VR urban environments during the experiments as they would do in the real world. Secondly, the VR-based test environments were created based on real urban areas from the dual perspective of geometry (layout) and characteristics such as the arrangement of buildings and the realism of the façades. This was to provide a consistently realistic setting for the experiments. Thirdly, is the control of the alternating sequencing in which participants experienced the two contrasting urban settings. The findings show that there was no consistent significant differences in the setting sequence amongst the participants in terms of their wayfinding behaviour as measured by distance travelled, time taken to complete, frequency of PDA spatial information access, time spent consulting PDA for the information and task planning times. These findings suggest that all participants exhibited consistent behaviour in completing wayfinding tasks and in using spatial information via the PDA. This is a positive sign that the data collected and analysed reflects participants' unaltered abilities during the wayfinding experiments in both test settings. Finally it should be reiterated that no participant had any prior knowledge of these areas. For these reasons, the experiments are considered to have validity in respect of their generalisable outcomes.

A series of detailed empirical wayfinding experiments concerning geographically extensive areas have been carried out using this methodology. The empirical data on interactions and information transactions thus generated have allowed a number of aspects of spatial information usage and wayfinding behaviour to be investigated in this research. Not only has every movement of the individual been tracked and their position plotted, but the frequency of spatial information access, the type of information accessed, when and where, and the time spent studying the information have all been quantified and analysed. The data make possible the investigation of wayfinding behaviour as expressed in route choice, distance travelled, time taken to complete, frequency of being lost/confused in the two contrasting urban settings. The data also enable the investigation of spatial information usage to be carried out when expressed as frequency of access, location of access, time spent and types of information consulted. In this respect, the conceptual model and the methodology used in its implementation have shown their advantages, not only at a theoretical level but also being applied empirically.

To reiterate for this discussion, the term 'spatial information usage' in this research refers to the situation where the spatial information is accessed and studied via a mobile device at real-time during wayfinding activities.

One aspect investigated in this research is the patterns of individual spatial information usage in assisting wayfinding. A set of variables have been elicited from the empirical data for describing the real-time usage of spatial information, including the frequency and time spent consulting the PDA for different types of spatial information, along with geographical position. Four distinct groups of individuals have been identified through the analysis of these variables (§8.6). Each of these four groups has marked differences in terms of their pattern of access and usage of spatial information via the PDA. These differences are statistically significant. These groups have been labelled as IN-G1 to IN-G4, where:

- Group IN-G1 with a preference for route information (sequential instructions).
- Group IN-G2 with a preference for maps, particularly more detailed localised map information.
- Group IN-G3 with mixed mode information, that is, either having an equal tendency to use route and map information or show greater flexibility in matching choice of information to the specific instances of spatial decision-making.
- Group IN-G4 with a strong preference for overview maps providing a more generalised spatial layout.

This grouping indicates that there are clear patterns of preferences in using different types of spatial information in wayfinding. These four groups are not just identifiable by their preference for particular types of spatial information, but also show discernable patterns in their temporal and spatial behaviour during wayfinding.

Whereas the preferences for particular types of information can be identified, the patterns of spatio-temporal usage also reveal that there are different but consistent strategies employed by individuals which reflect on the behaviour of the groups. Thus:

- For Group IN-G1, there is consistent reference to route information during the wayfinding tasks. However, where individuals encounter perceived difficulties or uncertainty either for planning the route or making choices at decision points, overview and detailed maps would be used with route information.
- For Group IN-G2, there is a pattern of using overview maps in conjunction with detailed maps for the planning of routes (at the start) but that all other information

along the route is acquired from detailed maps that provide localised information.

- For Group IN-G3, there is an alternation in using different types of information in different situations and settings. It appears that these individuals choose whatever suites their purpose in response to the surrounding environment.
- For Group IN-G4, overview maps are the dominant source of spatial information, with only very occasional use of alternative types of information. Individuals in this group are characterised by high frequency of spatial information access.

Moreover, the study indicates that the strategies used are consistent between the two contrasting urban settings. However the different urban settings did appear have an influence on the information usage strategies for Group IN-G3 as a consequence of their flexibility or willingness to change their information use in response to the changing situation.

From position/time data and PDA usage data, this study has identified a distinct period of higher spatial information access at the start of wayfinding tasks coupled with time spent in consulting and assimilating the information. This period is identified in this research as planning time. The planning time variable shows further differences between the groups and is an important aspect of their wayfinding strategies. Thus:

- For Group IN-G1, there is a tendency to take less time in planning the task more concentrating on the procedural route information and some detailed local layout that allows them to start quickly. Access of spatial information is more intensive along the routes as more information is required. This suggests a lack of configurational knowledge gained during task planning.
- For Group IN-G2, there is more time spent on planning tasks with some reference to overview maps but moving to detailed maps for local layout. Tasks tend to be planned sequentially with planning time equally distributed at the starting points of each successive task. This also suggests that the configurational knowledge gained is not spatially extensive but is locally focused.
- For Group IN-G3, there is time spent planning, however, overall there is a tendency to treat start points for tasks equally with decision points (such as road junctions) along the route.
- For Group IN-G4, there is considerable time spent on planning tasks with decreasing planning time used on successive tasks. This indicates that individuals within this group develop configurational knowledge of the area from their experience of the wayfinding.

Furthermore, complex settings and locations with more challenging spatial layouts tend to have more of an effect on individuals in Groups IN-G1 and IN-G3 in as much as they increase the frequency of spatial information access and change the type of information being accessed.

Another indication of differences between these groups has been evidenced through the sketch maps that capture their recall of spatial knowledge gained during the wayfinding tasks. Thus the individuals in Groups IN-G1 and IN-G2 do not seem to develop well structured configurational knowledge of the whole area. Recall of spatial knowledge and its representation as a sketch map can have its shortcomings (§3.4) but does nevertheless appear to be reflect self-assessed spatial ability. However, as identified in this research, self-assessed spatial ability does not appear to be the main determinant of patterns of spatial information usage strategies in wayfinding.

This new typology of spatial information usage groups has been shown to reflect a number of characteristics of wayfinding behaviour. These groups can be applied to a broader range of studies concerning the spatial information needs of individuals on the move. The four Groups have been further studied in relation to self-assessed spatial ability groups.

From the self-assessed questionnaires administered in this study, three different self-assessed spatial ability groups have been identified (§8.2) based on existing theoretical considerations. These three groups, SA-G1 to SA-G3 reflect low, intermediate and high self-assessed spatial ability respectively. This indicates that individual spatial ability may not be as clear cut as the binary divide of 'good' versus 'poor' ability as has previously been suggested.

The three SA Groups have been studied in relation to their wayfinding behaviour and in terms of their spatial information usage. The analysis indicates that the individuals with high self-assessed spatial ability (SA-G3) are more likely to familiarise themselves and study the spatial information from the mobile device (PDA) in the early stages of wayfinding. By contrast those individuals with low self-assessed spatial ability (SA-G1) are less likely to behave in this manner but tend to access information more frequently along the routes taken. Individuals in Group SA-G3 seem to have exercised more diversity in their route choices. Despite broad apparent similarities between SA and IN Groups, the cross tabulation of these two types of groups (§8.6) show that SA Groups are a poor predictor of preferences for spatial information usage as expressed in the IN Groups. Thus although self-assessed spatial ability groups give an indication of people's ability in respect of completing wayfinding tasks, they are not fully reflect the pattern of spatial information usage for assisting such wayfinding. This would suggest that spatial ability and, in particular, people's spatial information preferences are better determined through real-time data collection of wayfinding activities.

In this regard, measures of spatial information usage should be included as an integral indicator of individual spatial ability.

From the perspective of spatial knowledge acquisition discussed in §3.3, there are deemed to be three defined types of spatial knowledge: landmark, route and configurational knowledge. The groups based on spatial information usage (IN Groups) have preferences for route information, overview (synoptic) map information and detailed (localised) map information. In the usage of this information it is suggested that landmark are embedded and acting as part of route knowledge and configurational knowledge. Whilst the information in a detailed map may be considered as configurational, the evidence of this research is that such maps do not confer configurational knowledge to a great extent as they tend to represent only localised collections of landmarks.

Also from the self-assessed questionnaire, participants could be identified according to their tendency for route/landmark/map thinking. This research has shown that individuals with a tendency for route-orientated thinking also expressed a tendency for landmark-orientated thinking. The same was true of individuals with self-assessed map-orientated thinking. This further indicates that landmarks should be considered as an important element in all forms of spatial thinking.

Another aspect of this investigation has been the influence of urban morphology on individual wayfinding behaviour and spatial information usage. The attributes of the environment can have an important influence on wayfinding behaviour, and the VR-based approach has allowed such influences to be investigated in a systematic manner. In this research, two contrasting urban models with their own distinctive layouts and mix of architectures were used for the wayfinding experiments. Firstly, the effect of urban morphology on individual wayfinding behaviour has been analysed in terms of distance travelled, time taken to complete, time-distance relationships and route choices. There is a strong indication from these variables that the characteristics of spatial locations do have an influence on wayfinding behaviour. Also exhibited are the differences in wayfinding behaviour for each individual route. These differences can be quite marked (e.g. §8.4.4) and appears to vary according to the perceived complexity of each wayfinding task. Secondly, the effect of urban morphology on behaviour has been studied in terms of spatial information usage in wayfinding and found to have an influence on how spatial information is used for wayfinding. Significant differences were found between the two different urban settings in respect of the task planning time and the time spent on spatial information usage. Although the frequency of information access is higher in what would be considered the more challenging setting (U2), it is not statistically significant. The study also suggests that spatial layout and environment along the route do have an influence on frequency of PDA access and usage. Moreover, the study suggests that differences in urban layout seem to influence the pattern of information usage such as switching between different types of information. This is further supported by the patterns of spatial distribution of spatial information usage via the mobile device (§8.7).

Whilst this study has developed a number of important conclusions, a number of limitations to the study can be identified. Firstly, this study could have benefited from a larger sample. The funding obtained for the use of the VR facilities was limited to 30 participants. Three participants could not complete the experiments due to motion sickness. At an overall aggregate level, 27 participants have been sufficient for non-parametric statistical inference. However, at group level, the samples have sometimes been too small to statistically verify effects. Novel usage of a PDA for wayfinding and VR-based test environments may have been a distraction to participants. However, the findings would indicate that the experiments measured stable behaviour and does not appear to have been an effect from the feedback of the participants. For the urban models used in the VR-based test environments, there are no moving objects such as people, animals and vehicles. Whilst this may be construed as being artificial, it results in very little distraction during the wayfinding. One purpose of the VR test environments was to limit any confounding distractions that might otherwise occur is real world situations. It provides more a consistent setting for studying specific factors. VR does, however, have the drawback in that it can induce motion sickness. Finally, the methodology resulted in such a rich empirical data set, that it has not been possible to analyse all aspects within this thesis (but see future research below).

Whilst this research has achieved its aims and has answered a number of questions on the way spatial information, delivered to a mobile device, is used during pedestrian wayfinding, new questions have been provoked by these outcomes. The investigator has already received confirmation of an ESRC post-doctoral fellowship in order to explore these. Firstly, as intimated above, the volume of data generated by the methodology could not be analysed in all its aspects within the confines of this PhD thesis. Given space-time data on spatial information access, and the classification of preference groups already achieved, is it possible to develop a predictive model (either Markovian or Bayesian) of spatial information access? The results from this could result in some form of intelligent agent modelling. The VR urban settings could be enhanced with, for example, trees and vehicles (stationary and moving) as well as even people and used to conduct further experiments. Thus wayfinding and spatial information access behaviours could be studied for a broader range of age groups and for groups from different socio-economic and cultural backgrounds. Changes to building types, particularly height, within the same road geometry would allow investigation of any 3-D effect of urban morphology on wayfinding and spatial information usage. By changing certain parameters within the test settings it would be further possible to investigate the effects of day and night on individual wayfinding. Finally, whilst the current research has focused on the use of spatial information as text, voice and maps, an extended range of formats for spatial information as might be offered by multi-media could be studied.

This thesis has been a beginning, not an end.

This page is a blank thought!

References

Aitken, S. C. and Prosser, R. (1990) Residents' spatial knowledge of neighborhood continuity and form. *Geographical Analysis* 22: 301-325

Allen, G. L. (1997) From knowledge to words to wayfinding: issues in the production and comprehension of route directions. In *Spatial Information Theory: A Theoretical basis for GIS* (Hirtle and Frank eds.). Lecture Notes in Computer Science, Springer-Verlag, Brelin: 363-372

Allen, G. L. (1999a) Cognitive abilities in the service of wayfinding: a functional approach. *Professional Geographer* 51: 554-561

Allen, G. L. (1999b) Spatial abilities, cognitive maps, and wayfinding: bases for individual differences in spatial cognition and behavior. In *Wayfinding Behavior: Cognitive Mapping and Other Spatial Processes* (Golledge ed.). The Johns Hopkins University Press, Baltimore: 46-80

Allen, G. L., Kirasic, K. C., Dobson, S. H., Long, R. G. and Beck, S. (1996) Predicting environmental learning from spatial abilities: an indirect route. *Intelligence* 22: 327-355

Appelle, S. (1972) Perception and discrimination as a function of stimulus orientation: The "oblique effect" in man and animals. *Psychological Bulletin* 78: 266-278

Authur, P. and Passini, R. (1992) *Wayfinding: People, Signs and Architecture*. McGraw-Hill Publishing Company, New York.

Banz, G. (1970) *Elements of Urban Form*. McGraw Hill, New York.

Batty, M. (1990) Intelligent cities: using information networks to gain competitive advantage. *Environment and Planning B* 17: 247-256

Batty, M. (1993) The geography of cyberspace. *Environment and Planning B* 20: 615-661

Batty, M. and Smith, A. (2002) Virtuality and cities: definitions, geographies, designs. In *Virtual Reality in Geography* (Fisher and Unwin eds.). Taylor & Francis, London: 270-291

Batty, M., Dodge, M., Doyle, S. and Smith, A. (1998) Modelling virtual environments. In *Geocomputation: A Primer* (eds. Longly, Brooks, McDonnell and Macmillan), Willey, Chichester: 138-161

Batty, M., Fairbairn, D, Ogleby, C., Moore, K. and Taylor, G. (2002) Virtual cities: introduction. In *Virtual Reality in Geography* (eds, Fisher and Unwin), Taylor & Francis, London: 211-219

Berry, J. W. (1966) Temne and Eskimo perceptual skills. *International Journal of Psychology* 1: 207-229

Berthoz, A., Israel, I., Georges-Francois, P., Grasso, R. and Tsuzuki, T. (1995) Spatial memory of body linear displacement: What is being stored? *Science* 269: 95-98

Bishop, I. D., Ye, W. S. and Karadiglis, C. (2001) Experimental approaches to perception response in virtual worlds. *Landscape and Urban Planning* 54: 119-127

Blades, M. (1991) Wayfinding theory and research: The need for a new approach. In *Cognitive and Linguistic aspects of Geographic Space* (Marks and Frank eds.). Kluwer Academic Publishers, Dordrecht: 137-165

Bovy, P. H. L. and Stern, E. (1990) *Route Choice: Wayfinding in Transport Networks*. Kluwer Academic, Dordrecht.

Braun, P. (2003) *Primer on Wireless GIS*. URISA, Park Ridge, IL.

Brimicombe, A. J. (1999) Encoding expert opinion in Geo-Information systems: a fuzzy set solution. *Transactions in International Land Management* 1: 105-121

Brimicombe, A.J. and Li, Y (2006) Mobile space-time envelopes for Location-Based Services. *Transactions in GIS* (forthcoming)

Bryant, K. J. (1982) Personality correlates of sense of direction and geographic orientation. *Journal of Personality & Social Psychology* 43(6): 1318-1324

Burrough, P. A. (2000) Whither GIS (as systems and as science)? *Computers, Environment & Urban Systems* 24: 1-3

Byant, K. J. (1991) Geographical/spatial orientation ability within real-world and simulated large-scale environments. *Multivariate Behavioral Research* 26: 109-136

Bystrom, K. E., Barfield, W. and Hendrix, C. (1999) A conceptual model of the sense of presence in virtual environments. *Presence: Teleoperators and Virtual Environment* 8(2): 241-244

Campari, I. and Frank, A. U. (1993) Cultural differences in GIS: A basic approach. *Proceedings of Fourth European Conference and Exhibition on Geographical Information Systems*: 10-16

Casey, E. S. (2001) Between geography and philosophy: what does it mean to be in the place-world. *Annals of the Association of American Geographers* 91: 683-693

Castells, M. (1989) *The Informational City*. Blackwell, Oxford.

Castells, M. (1996) *The Rise of the Network Society*. Blackwell, Oxford.

Chu, K. K. W. (2002) Users with small screens – less than 640x480. *Universal Usability in Practice*. http://www.otal.umd.edu/uupractice/samll_screen/ last view in November 2004

Cornell, E., Sorenson, A. and Mio, T. (2003) Human sense of direction and wayfinding. *Annals of the Association of American Geographers* 93(2): 399-425

Cote, P. (2005) Rendering multiple urban design scenarios from a single database of 3D features. In *CUPUM05: Computers in Urban Planning and Urban Management* (ed. Batty): 319

Cruz-Neira, C., Sandin, D. J., DeFanti, T. A., Kenyon, R. V. and Hart, J. C. (1992) The CAVE: audio visual experience automatic virtual environment. *Communications of the ACM* 36(5): 65-72

Denis, M., Pazzaglia, F., Cornoldi, C. and Bertolo, L. (1999) Spatial discourse and navigation: an analysis of route directions in the city of Venice. *Applied Cognitive Psychology* 13: 145-174

Dey, A. K. (2001) Understanding and using context. *Personal and Ubiquitous Computing Journal* 5 (1): 4-7

Dodge, M. and Kitchin, R. (2000) *Mapping Cyberspace*. Taylor and Francis, London.

Doherty, S., Gale, N. D., Pellegrino, J. W. and Golledge, R. G. (1989) Children's vs. adult's knowledge of places and distances in a familiar neighborhood environment. *Children's Environments Quarterly* 6: 65-71

Downs, R. M. (1970) Geographic space perception: past approaches and future prospects. *Progress in Geography* 2: 65-108

Downs, R. M. and Stea, D. (1973) *Image and Environment: Cognitive Mapping and Spatial Behavior*. Aldine Publishing Company, Chicago.

Draper, J. V., Kaber, D. B. And Usher, J. M. (1998) Telepresence. *Human Factors* 40(3): 354-375

Egenhofer, M. J. (1991) Deficiencies of SQL as a GIS query language. In *Cognitive Linguistic Aspects of Geographic Space* (Marks and Frank eds.). Kluwer Academic Publishers, Dordrecht: 477-491

Ellis, S. R. (1991) Nature and origin of virtual environments: a bibliographic essay. *Computing Systems in Engineering* 2(4): 321-47

Evans, G. W. (1980). Environmental Cognition. *Psychological Bulletin* 88: 259-287

Federal Communications Commission (2001) FCC wireless 911 requirements. www.fcc.gov/e911/ as viewed on 3/01/2002

Fisher, P. and Unwin, D. (eds.) 2002 *Virtual Reality in Geography*. Taylor & Francis, London

Fogli, D., Pittarello, F., Celentano, A. and Mussio, P. (2003) Context-aware interaction in a mobile environment. *Mobile HCI 2003*. Springer-Verlag, Berlin: 116-130

Fowler, H. W. and Fowler, F. G. (1995) *The Concise Oxford Dictionary of Current English*. Clarendon Press, Oxford.

Frank, A. (2003) Pragmatic information content – how to measure the information in a route description. In *Foundations of Geographic Information Science* (eds. Duckham, Goodchild and Worboys). Taylor & Francis, London: 47-68

Frank, A. U. (1992) Qualitative spatial reasoning about distances and directions in geographic space. *Journal of Visual Languages and Computer* 3: 343-371

Freeman, J., Avons, S. E., Medis, R., Pearson, D. E. and IJsselsteijn, W. A. (2000) Using behavioural realism to estimate presence: A study of the utility of postural responses to motion-stimuli. *Presence: Teleoperators and Virtual Environments* 9(2): 149-164

French, J. W., Ekstrom, R. B. and Price, L. A. (1963) *Kit of Reference Tests for Cognitive Factors. Educational Testing Services*. Princeton, NJ.

Gale, N. D., Golledge R. G., Pellegrino, J. W. and Doherty, S. (1990) The acquisition and integration of neighborhood route knowledge. *Journal of Experimental Psychology* 10: 3-26

Gärling, T. & Golledge, R. G. (1987) Environmental perception and cognition. In *Advances in Environment, Behavior and Design* (Zube and Moore eds.). Plenum Press, New York: 203-236

Gärling, T., Böök, A. and Lindberg, E. (1984) Cognitive mapping of large-scale environments: The interrelationship of action plans, acquisition, and orientation. *Environment and Behavior* 16: 3-34

Gärling, T., Bőők, A., Linberg, A. and Nilsson T. (1981) Memory for the spatial layout of the everyday physical environment: factors affecting the rate of acquisition. *Journal of Experimental Psychology* 1: 263-277

Gartner G 2004 Location-based mobile pedestrian navigation services – the role of multimedia cartography. *ICA UPIMap2004*. Tokyo.

Giaglis, G., Kourouthanasis, P. and Tsamakos, A. (2002). Towards a classification network for mobile location services. In *Mobile Commerce: Technology, Theory, and Applications* (eds. Mennecke and Strader). Idea Group Publishing: 64-81

Gibson, J. J. (1979) *The Ecological Approach to Visual Perception*. Houghton Mifflin, Boston MA.

Giraudo, M. and Pailhous, J. (1994) Distortions and fluctuations in topographic memory. *Memory and Cognition* 22:14-26

Gladwin, T. (1970) *East is a Big Bird*. Harvard University Press, Cambridge MA.

Gluck, M. (1991) Making sense of human wayfinding: review of cognitive and linguistic knowledge for personal navigation with a new research direction. In *Cognitive and*

Linguistic Aspects of Geographic Space (Mark and Frank eds.). Kluwer, Dordrecht: 117-135

Gold, J. R. (1980) *An Introduction to Behavioural Geography*. Oxford University Press, New York.

Golledge, R. G. (1978) Learning about urban environments. In *Timing Space and Spacing Time I: Making Sense of Time* (Carlstein et al., eds.). Edward Arnold, London: 76-98

Golledge, R. G. (1992) Place recognition and wayfinding: Making sense of space. *Geoforum* 23(2): 199-214

Golledge, R. G. and Stimson R. J. (1987) *Analytic Behavioral Geography*. Croom Helm, London.

Golledge, R. G. and Stimson R. J. (1997) *Spatial Behavior: A Geographic Perspective*. The Guilford Press, New York.

Golledge, R. G., Dougherty, V. and Bell, S. (1995) Acquiring spatial knowledge: survey versus route-based knowledge in unfamiliar environments. *Annals of the Association of American Geographers* 85: 134-158

Golledge, R. G., Smith, T. R., Pellegrino, J. W., Doherty, S. and Marshall, S. P. (1985) A conceptual model and empirical analysis of children's acquisition of spatial knowledge. *Journal of Environmental Psychology* 5: 125-152

Golledge. R. G. and Spector, A. N. (1978) Comprehending the urban environment: theory and practice. *Geographical Analysis* 10: 403- 426

Goodchild, M. F. (1990) Keynote address: spatial information science. *Proceedings 4th International Symposium on Spatial Data Handling*. VI: 13-14

Goodchild, M. F. (1992) Geographical information science. *International Journal of Geographical Information Systems* 6: 31-45

Gould, P. (1975) Acquiring spatial information. *Economic Geography* 51: 87-99

Graham, S. (1998) The end of geography or the explosion of place: Conceptualizing space, place and information technology. *Progress in Human Geography* 22: 165-185

Grejner-Brzezinska, D. (2004) Positioning and tracking approaches and technologies. In *Telegeoinformatics: Location-Based Computing and Services* (eds. Karimi and Hammad). CRC Press, Boca Raton: 69-110

Griffith, D. A. and Amrhein, C. G. (1991) *Statistical Analysis for Geographers*. Prentice Hall, Englewood Cliffs NJ.

Hart, R. A. and Moore, G. T. (1973) The development of spatial cognition: a review. In *Image and Environment* (Downs and Stea, ed.). Aldine, Chicago: 246-288

Hazem. N. L. (1983) Spatial orientation: a comparative approach. In *Spatial Orientation: Theory, Research, and Application* (Pick and Acredolo, eds.). Plenum Press, New York: 3-37

Heft, H. (1983) Wayfinding as the perception of information over time. *Population and Evnirnment* 6: 133-150

Hegarty, M., Richardson, A. E., Montello D. R., Lovelace, K. and Subbiah, I. (2002) Development of a Self-Report Measure of Environmental Spatial Ability. *Intelligence* 30: 425-447

Held, R. M. and Durlach, N. I. (1992) Telepresence. *Presence: Teleoperators and Virtual Environments* 1(1): 109-112

HPLabs (2001) The challenges and opportunities of integrating the physical world and networked systems. *http://cooltown.hp.com/dev/wpapers/webpres/* as viewed on 13th Sept. 2001

Hunt, M. E. and Waller, D. (1999) *Orientation and Wayfinding: A review* (ONR technical report N00014-96-0380). Office of Naval Research, Arlington, VA.

James, W. (1890) *The Principles of Psychology*. Macmillan, London: 204

Kato, Y. and Takeuchi, Y. (2003) Individual differences in wayfinding strategies. *Journal of Environmental Psychology* 23: 171-188

Kirk, W. (1963) Problems of geography. *Geography* 48: 357-371

Kitchin, R. (1996) Increasing the integrity of cognitive mapping research: appraising conceptual schemata of environment - behaviour interaction. *Progress in Human Geography* 20: 56-84

Kitchin, R. (1998) Towards geographies of cyberspace. *Progress in Human Geography* 22: 385-406

Kitchin, R. and Blades, M. (2002) *The Cognition of Geographic Space*. I.B.Tauris Pbulishers, London.

Kozlowski, L. T. and Bryant K. J. (1977) Sense of direction, spatial orientation and cognitive maps. *Journal of Experimental Psychology: Human Perception and Performance* 4: 590-598

Kuipers, B. (1978) Modeling spatial knowledge. *Cognitive Science* 2: 129-153

Kuipers, B. (1983a) The cognitive map: Could it have been any other way? In *Spatial Orientation: Theory, Research and Application* (Pick and Acredolo, eds.). Plenum Press, New York: 345-359

Kuipers, B. (1983b) Modeling human knowledge of routes: Partial knowledge and individual variation. *Proceedings of the National Conference on Artificial Intelligence*. AAAI 1983 Conference: 1-4

Lathrop, O. (1999) *Virtual Reality*. www.inf.ed.ac.uk/teaching/courses/cg/web/intro-graphics/vr.html (last viewed in July 2005)

Lewis, D. (1972) *We the Navigators*. Australian Ntional University Press, Canberra.

Li, C. and Maguire, D. (2003) The handheld revolution: towards ubiquitous GIS. In *Advanced Spatial Analysis: The CASA Book of GIS* (eds. Longley and Batty). ESRC Press: Redlands CA: 193-210

Liben, L. S. (1997) Children's understanding of spatial representations of place: mapping the methodological landscape. In *A Handbook of Spatial Research Paradigms and Methodologies, Vol 1: Spatial Cognition in the Child and Adult* (eds. Foreman and Gillet). Lawrence Erlbaum Association Inc., Hove: 41-83

Likert, R. and Quasha, W. H. (1941) *Revised Minnesota Paper Form Board.* Psychological Corporation, New York.

Lloyd, R. (1976) Cognition, preference, and behaviour in space: an examination of the structureal linkages. *Economic Geography* 52: 241-253

Lloyd, R. (1989) Cognitive maps: encoding and decoding information. *Annals of the American Association of American Geographers* 79: 101-124

Lohman, D. F. (1988) Spatial abilities as traits, processes, and knowledge. In *Advances in the Psychology of Human Intelligence* 4 (Sternberg ed.). Lawrence Erlbaum, Hillsdale, NJ: 181-248

Longley, J. M. (1967) An appraisal of least-squares programs for the electronic computer from the point of view of the users. *Journal of the American Statistical Association. 62:* 819-829

Longley, P. L., Goodchild, M. F., Maguire, D. J. and Rhind D. W. (2001) *Geographic Information Systems and Science*. Willey, Chichester, (1st Edition).

Longley, P. L., Goodchild, M. F., Maguire, D. J. and Rhind D. W. (2005) *Geographic Information Systems and Science*. Willey, Chichester, (2nd Edition).

Loomis, J. M., Klatzky, R. L. Colledge, R. G. and Philbeck, J. W. (1999) Human navigation by path integration. In *Wayfinding behavior: Cognitive Mapping and Other Spatial Processes* (ed. Golledge). Johns Hopkins Press, Baltimore: 125-151

Lorenz, C. A. and Neisser, U. (1986) Ecological and psychometric dimensions of spatial ability. *Technical Report No. 10 Emory Cognition Project*, Emory University, Atlanta, GA.

Lovelace, K., Hegarty, M and Montello, D. (1999) Elements of good route directions in familiar and unfamiliar environments. In *Spatial Information Theory, Cognitive and Comutational Foundation of Geographic Information Science* (eds. Freksa and Mark). Springer, Berlin: 65-82

Lovett, A. (2005) Futurescapes. *Computers, Environment and Urban Systems* 29(3): 249-253

Lynch, K. (1960) *The Image of the City*. MIT Press, Cambridge, Massachusetts.

MacEachren, A. M. (1992) Application of environmental learning theory to spatial knowledge acquisition from maps. *Annals of the Association of American Geographers* 82: 245-274

Malinowski, J. C. and Gillespie, W. T. (2001) Individual differences in performance on a large-scale, real-world wayfinding task. *Journal of Environmental Psychology* 21: 73-82

Mallot, H. A., Steck, S. D. and Loomis, J. M. (2002) Mechanisms of spatial cognition: behavioural experiments in virtual environments. KI 4/2002: *Spatial Cognition*: 24-28

Mark, D. M. (1993) Toward a theoretical framework for geographic entity types. In *Spatial Information Theory: A Theoretical Basis for GIS* (Frank and Campari, eds.). Springer-Verlag, Berlin: 312-321

Mark, D. M. (1999) Spatial representation: a cognitive view. In *Geographical Information Systems* (Longley, Goodchild, Maguire, Rhind eds.). Wiley, New York: volume 1, 81-89

Mark, D. M. (2003) Geographic information science: defining the field. In *Foundations of Geographic Information Science* (Duckham, Goodchild and Worboys eds.). Taylor & Francis, London: 3-18

Masters, M. S. and Sanders, B. (1993) Is the gender differences in mental rotation disappearing? *Bahavior genetics* 23(4): 337-341

Mather, P. M. (1976) *Computational Methods of Multivariate Analysis in Physical Geography*. Willey, London.

May, M., Pèruch, P. and Savoyant, A. (1995) Navigating in a virtual environment with map-acquired knowledge: encoding and alignment effects. *Ecological Psychology* 7: 21-36

McGee, M. G. (1979) Human spatial abilities: psychometric studies and environmental, genetic, hormonal, and neurological influences. *Psychological Bulletin* 86(5): 889-918

McMaster, R. B. and Shea, K. S. (1992) *Generalization in Digital Cartography*. Association of American Cartographers, Washington, DC.

Meehan, M., Insko, B., Whitton, M. and Brooks, F. P. (2002) Physiological measures of presence in stressful virtual environments. *ACM Transactions on Graphics, Proceedings of ACM SIGGRAPH 2002* 21(3): 645-653

Milgram, S. and Jodolet, D. (1976) Psychological maps of Paris. In *Environmental Psychology* (Proshansky and Ittelson eds.). Holt, Rinehart and Winston, NY.

Minsky, M. A. (1975) A framework for representing knowledge. In *The Psychology of Computer Vision* (Winston ed.). McGraw-Hill, New York.

Moeser, S. D. (1988) Cognitive mapping in a complex building. *Environment and Behavior* 20: 21-49

Montello, D. R. (1991) The measurement of cognitive distance: methods and construct validity. *Journal of Environmental Psychology* 11: 101-122

Montello, D. R. (1995) How significant are cultural differences in spatial cognition? In *Spatial Information Theory* (Frank and Kuhn, eds.). Springer-Verlag, Berlin: 485-500

Montello, D. R. (1998) A new framework for understanding the acquisition of spatial knowledge in large -scale environments. In *Spatial and Temporal Reasoning in Geographic Information Systems* (Egenhofer and Golledge eds.) Oxford University Press, New York: 143-154

Montello, D. R. (2001) Spatial cognition. In *International Encyclopedia of the Social & Behavioral Science* (eds. Smelser and Baltes). Pergamon Press, Oxford: 14771-14775

Montello, D. R. and Pick, H. L. (1993) Integrating knowledge of vertically aligned large-scale spaces. *Environment and Behavior* 25: 457-484.

Montello, D. R., Hegarty, M., Richardson, A. E. and Waller, D. (2004) Spatial memory of real environments, virtual environments, and maps. In *Human Spatial Memory: Remembering Where* (ed. Allen), Lawrence Erlbaun Associates, Mahwah, NJ: 251-285

Montello, D. R., Lovelace, K. L., Golledge, R. G. and Self, C. M. (1999) Sex-related differences and similarities in geographic and environmental spatial abilities. *Annals of the Association of American Geographers* 89: 515-534

Moss, M. and Townsend, A. M. (2000) How telecommunications systems are transforming urban spaces. In *Cities in the Telecommunications Age: The Fracturing of Geographies* (Wheeler, Aoyama and Warf eds.). Routledge, New York: 31-41

Mountain, D. and Raper J. (2001) Modelling human spatio-temporal behaviour: a challenge for location-based services. *Proceedings of the 6th International Conference on GeoComputation*. University of Queensland, Brisbane.

Muller, J-C., Lagrange, J-P. and Weibel, R. (eds.) (1995) *GIS and Generalization: Methodology and Practice*. Taylor & Francis, London.

Murray, C. D., Bowers, J. M., West, A. J., Pettifer, S. and Gibson, S. (2000) Navigation, wayfinding, and place experience within a virtual city. *Presence: Teleoperators and Virtual Environments* 9(5): 435-447

Neisser, U. (1976) *Cognition and Reality*. Freeman, Francisco.

Nielsen, J. (1993) *Usability Engineering*. Morgan Kaufmann, San Diego.

Norman, D. (1988) *The Design of Everyday Things*. Doubleday, New York.

Ordnance Survey (2001) *OS MasterMap™ Real-World Object Catalogue*. Ordnance Survey, Southampton.

Oulasvirta, A., Kurvinen, E. and Kankainen, T. (2003) Understanding contexts by being there: case studies in bodystorming. *Personal and Ubiquitous Computing* 7 (5): 125-134

Paay, J. (2003) Understanding and modelling physical environments for mobile location aware information services. *Mobile HCI 2003*. Springer-Verlag, Berlin: 405-410

Pacione, M. (1978) Information and morphology in cognitive maps. *Transactions of the Institute of British Geographers* NS 3: 548-568

Pazzaglia, F. and De Beni, R. (2001) Strategies of processing spatial information in survey and landmark-centred individuals. *European Journal of Cognitive Psychology* 13 (4): 493-508

Peng, Z. R. and Tsou, M. H. (2003) *Internet GIS: Distributed Geographic Information Services for the Internet and Wireless Networks*. Wiley, Hoboken, NJ.

Pertaub, D. P., Slater, M. and Barker, C. (2002) An experiment on public speaking anxiety in response to three different types of virtual audience. *Presence: Teleoperators and Virtual Environments* 11(1): 68-78

Piaget, J. and Inhelder, B. (1956) *The Child's Conception of Space*. Routledge and Kegan Paul, London.

Pocock, D. C. D. (1973) Environmental perception: process and product. *Tijdschrift Voor Econmische en Social Geografie* 64: 251-157

Preece, J., Rogers, Y., Sharp, H., Benyon, D., Holland, S. and Carey, T. (1994) *Human-Computer Interaction*. Addison-Wesley, Harlow.

Presson, C. C. and Hazelrigg, M. D. (1984) Building spatial representations through primary and secondary learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition* 10: 716-722

Prestopnik, J. L. and Roskos-Ewoldson, B. (2000) The relations among wayfinding strategy use, sense of direction, sex, familiarity, and wayfinding ability. *Journal of Environmental Psychology* 20: 177-191.

Raubal, M and Egenhofer, M. J. (1998) Comparing the complexity of wayfinding tasks in built environments. *Environment and Planning B: Planning and Design* 25: 895-913

Relph, E. (1976) *Place and Placelessness*. Pion, London.

Rohrmann, B., and Bishop, I. (2002) Subjective responses to computer simulations of urban environments. *Journal of Environmental Psychology* 22: 319-331

Rosch, R. and Mervis, C. B. (1975) Desert ants (cataglyphis fortis) use self-induced optic flow to measure distances travelled. *Journal of Comparative Physiology* A177: 21-27

Rossano, M. J. and Moak, J. (1998) Spatial representations acquired from computer models: cognitive laod, orientation specificity and the acquisition of survey knowledge. *British Journal of Psychology* 89: 481-497

Rossano, M. J., West, S. O., Robertson, T. J.; Wayne M. C. and Chase, R. B. (1999) The acquisition of route and survey knowledge from computer models. *Journal of Environmental Psychology* 19: 101-115

Rothbaum, B. O., Hodges, L. F., Kooper, R., Opdyke, D., Williford, J. and North, M. M. (1995) Effectiveness of computer-generated (virtual reality) graded exposure in the treatment of acrophobia. *American Journal of Psychiatry* 152: 626-628

Ruddle, R. A. and Peruch, P. (2004) Effects of proprioceptive feedback and environmental characteristics on spatial learning in virtual environments. *International Journal of Human-Computer Studies* 60: 299-326

Ruddle, R. A., Payne, S. J. and Jones, D. M. (1997) Navigating buildings in 'desk-top' virtual environments: experimental investigations using extended navigational experience. *Journal of Experimental Psychology: Applied* 3: 143-159

Sage, A. (2001) Future positioning technologies and their application to the automotive sector. *The Journal of Navigation* 54: 321-328

Sandstrom, N. J., Kaufman, J. and Huettel, S. A. (1998) Males and females use different distal cues in a virtual environment navigation task. *Cognitive Brain Research* 6: 351-360

Schlender, D., Peters, O. and Wienhöfer, M. (2002) The effects of maps and textual information on navigation in a desktop virtual environment. *Spatial Cognition and Computation* 2: 421-433

Schmidt, A and Van Laerhoven, K. (2001) How to build smart appliances? *IEEE Personal Communications* 8(4): 66-71

Self, C. M. and Golledge, R. G. (1994) Sex-related differences in spatial ability: what every geography educator should know. *Journal of Geography* 93(5): 234-243

Self, C. M., Gopal, S., Golledge, R. G. and Fenstermaker, S. (1992) Gender-related differences in spatial abilities. *Progress in Human Geography* 16: 315-342

Shemyakin, F. N. (1962) General problems of orientation in space and space representations. In *Psychological Sciences in the USSR* Vol.1 (Anan'yev *et al.* eds.), NTIS Report No. TT62-11083, Office of Technical Services, Washington DC: 184-225

Shepard, R. N. and Hurwitz, S. (1984) Upward direction, mental rotation, and discriminationof left and right turns in maps. *Cognition* 18: 161-193

Shepard, R. N. and Metzler, J. (1971) *Mental rotation of three-dimensional objects.* Science 171: 701-703

Sheridan, T. B. (1992) Musings on telepresence and virtual presence. *Presence: Teleoperators and Virtual Environments* 1(1): 120-126

Sholl, M. J. (1988) The relationship between sense of direction and mental geographic updating. *Intelligence* 12(3): 299-314

Sholl, M. J., Acacio, J. C., Makar, R. O. and Leon, C. (2000) The relation of sex and sense of direction to spatial orientation in an unfamiliar environment. *Journal of Environmental Psychology* 20: 17-28.

Siegel, A. W. and White, S. H. (1975) The development of spatial representations of large-scale environments. In *Advances in Child Development and Behavior* (Reese ed.), Academic Press, New York: 9-55

Silverman, I. and Eals, M. (1992) Sex differences in spatial ability: Evolutionary theory and data In *The Adapted Mind: Evolutionary Psychology and the Generation of Culture* (Barkow, Cosmides and Tooby eds.). Oxford University Press, New York: 533-549

Slater, M. and Steed, A. (2000) A virtual presence counter. *Presence: Teleoperators and Virtual Environment.* 9(5): 413-434

Slater, M., Steed, A. and Chrysanthou, Y. (2002) *Computer Graphics and Virtual Environments: from Realism to Real-Time.* Pearson, Harlow.

Spector, P. E. (1981) *Research Designs Series: Quantitative Applications in the Social Sciences.* SAGE Publications, Newbury Park, California.

Spencer, C., Blades, M. and Morsley, K. (1989) *The child in the Physical Environment: The Development of Spatial Knowledge and Cognition.* JohnWiley & Sons, Chichester.

Stea, D. (1967) The reasons for out moving. *Landscape* 17: 27-28

Steck, S. D. and Mallot, H. A. (2000) The role of global and local landmarks in virtual environment navigation. *Presence: Teleoperators and Virtual Environments* 9(1): 69-83

Stern, E. and Leiser, D. (1988) Levels of spatial knowledge and urban travel modeling. *Geographical Analysis* 20: 140-155

Stumpf, H. (1993) Performance factores and gender-related differences in spatial ability: another assessment. *Memory and Cognition* 21(6): 828-836

Swapp, D. (2004) Personal communication. Dr. David Swapp, CAVE manager, Department of Computer Science, University College London.

Takeuchi, Y. (1992) Sense of direction and its relationship with geographical orientation, personality traits and mental ability. *Japanese Journal of Education Psychology* 40: 47-53

Taylor, H. A. and Tversky, B. (1996) Perspective in spatial descriptions. *Journal of Memory and Language* 35: 371-391

The Commission of the European Communities (2003) Commission recommendation on the processing of caller location in electronic communication. *Official Journal of the European Union* 189: 49-51

Thorndyke, P. W. and Hayes-Roth, B. (1982) Differences in spatial knowledge acquired from maps and navigation. *Cognitive Psychology* 14: 560-589

Tlauka, M. and Wilson, P. N. (1996) Orientation-free representations from navigation through a computer-simulated environment. *Environment and Behavior* 28: 647-664

Tolman, E. C. (1948) Cognitive maps in rats and man. *Psychological Review* 55: 189-208

Tromp, J., Bullock, A., Steed, A., Sadagic, M., Slater, M. and Frécon, E. (1998) Small group behaviour experiments in the COVEN project. *IEEE Computer Graphics and Applications* 18: 53-63

Trowbridge, C. C. (1913) On fundamental methods of orientation and imaginary maps. *Science* 38: 888-897

Tuan, Y-F. (1974) Space and place: humanistic perspectives. *Progress in Geography* 6: 211-252

Tuan, Y-F. (1977) *Space and Place: The Perspective of Experience.* Edward Arnold Ltd., London.

Tversky, B., Morrison, J. B. Franklin, N. and Bryant, D. J. (1999) Three spaces of spatial cognition. *The Professional Geographers* 51: 516-524

Usoh, M., Catena, E., Arman, S. and Slater, M. (2000) Presence questionnaires in reality. *Presence: Teleoperators and Virtual Environments* 9(5):497-503

van Es, P. (2001) Where is the LBS industry heading to? *GI News April/May Issue*: 3-5

Van Veen, H. A., Distler, H. K., Braun, S. J. And Bulthoff, H. H. (1998) Navigating through a virtual city: using virtual reality technology to study human action and perception. *Future Generation Computer Systems* 14: 231-242

Vandenberg, S. G. and Kuse, A. R. (1978) Mental rotations: group test of three-dimensional spatial visualization. *Perceptual and Motor Skills* 47: 599-604

Vinayagamoorthy, V., Brogni, A., Gillies, M., Slater, M. and Steed, A. (2004) An investigation of presence response across variations in visual realism. *Presence 2004: The 7th Annual International Workshop on Presence*. Technical University of Valencia, Valencia, Spain.

Wallace, R. (1989) Cognitive mapping and the origin of lanuage and mind. *Current Anthropology* 30: 518-526

Walmsley, D. J. and Lewis, G. J. (1984) *Human Geography: Behavioural Approaches*. Longman Scientific & Technical, Harlow.

Walmsley, D. J., Saarinen, T. G. and MacCabe, C. L. (1990) Down under or centre stage? The world images of Australian students. *Australian Geographer* 21(2): 164-173

Ward, J. H. (1963) Hierarchical grouping to optimize an objective function. *Journal of the American Statistical Association* 58: 236

Wilson, P. N. (1997) Use of virtual reality computing in spatial learning research. In *A Handbook of Spatial Research Paradigms and Methodologies, Vol 1: Spatial Cognition in the Child and Adult* (eds. Foreman and Gillet). Lawrence Erlbaum Association Inc., Hove: 181-206

Witmer, B. G. and Singer, M. J. (1998) Measuring presence in virtual environments: a presence questionnaire. *Presence: Teleoperators and Virtual Environment* 7(3): 225-240

Witmer, B. G., Bailey, J. H., Knerr, B. W. and Parsons, K. C. (1996) Virtual spaces and real world places: transfer of route knowledge. *International Journal of Human-Computer Studies* 45: 413-428

Witmer, B. G., Sadowski, W. J. and Finkelstein, N. M. (2002) VE-based training strategies for acquireing survey knowledge. *Presence: Teleoperators and Virtual Environment* 11(1): 1-18

Wunderlich, D. and Reinelt, R. (1982) How to get there from here. In *Speech, Place, and Action* (Jarvella and Klein eds.). Wiley, Chichester: 183-201

Zahoric, P. and Jenison, R. L. (1998) Presence and being-in-the-world. *Presence: Teleoperators and Virtual Environment.* 7(1): 78-89

Zeimpekis, V., Giaglis, G. and Lekakos, G. (2003) A taxonomy of indoor and outdoor positioning techniques for mobile location services. *ACM SIGECOM Exchanges*, 3(4): 19-27

Zipf, A. (2002) User-adaptive maps for Location-Based Services (BLS) for tourism. *Proceedings 9th International Information and Communication in Tourism.* Springer, Heidelberg

Appendix I Information provided prior to the experiments

Information Sheet:

Dear Sir/Madam,

<u>Wayfinding Experiment in Virtual Reality</u>

Thank you for agreeing to participate in this experiment. Your participation is important to me and I think that you will find it interesting. This set of experiments is part of my PhD research work. The broad objective is to collect data on how people carry out wayfinding tasks using map and/or handheld electronic devices in urban environments. These environments are presented in a virtual reality laboratory. Participants will need to wear a shutterglasses and to use joystick-like device in order to move around the test areas. No previous experience of virtual reality is required.

<u>All the information that you provide and that be collected during the experiments will be treated in strict confidence, and you will not be individually identifiable in the results in any way.</u>

The following is a brief description of the experiment, which will give you an idea of the whole process. Please read it before you participate.

The whole experiment is conducted in four parts:

- **Start questionnaire**: There are no right or wrong answers to the questions on the first page. Most of the questions are about what you think or do as an individual during normal wayfinding tasks.
- **Wayfinding quest in urban environment Setting 1**: You will start from a car park and 'walk' through virtual reality to a castle, a church, a bank of your choice in Market Square, 'SuperMart' superstore, the George & Dragon pub and back to the car park. There are maps of the area, text instructions and voice instructions available for you to use depending on your preference. These are available through the electronic handheld device. You can rest whenever you want during the wayfinding quest, and you will be asked to take a short break after you have finished with Setting 1.
- **Wayfinding quest in urban environment Setting 2**: This will have similar wayfinding tasks to Setting 1 but in a totally different setting. You will again start from a car park 'walk' to a church, a post office, a McDonalds, a cinema, a monument, and return to the car park. As previously, there are maps, text instructions and voice instructions available for your use.

  During the two wayfinding quests, it would be helpful if you could speak aloud your thoughts and emotions in finding your way around the two Settings.

- **Debrief questionnaire and interview**: Again there are no right or wrong answers to the questions, which intend to ascertain your experience and opinions about the experiments. One part will be carried out after wayfinding in Setting 1, with the second part after wayfinding in Setting 2.

There will be a training session before the main experiment starts, in order to familiarise you with moving around the virtual environment and with acquiring information through the handheld electronic device. In accordance with UCL regulations, you will be required to sign a Consent Form (sample attached) prior to starting. You are free to withdraw from this experiment at any time and without giving any reason.

Thank you and I hope you will find the experiment interesting and enjoyable.

Yours sincerely,

(Lily) Chao Li
PhD Candidate
Centre for Advanced Spatial Analysis, University College London,
1-19 Torrington Place, London

Consent Form:

Wayfinding Experiment Consent Form

Please read and answer the following questions carefully:

Have you read the information sheet about this study?	YES / NO
Have you had an opportunity to ask questions about the procedure?	YES / NO
Have you received satisfactory answers to all your questions?	YES / NO
Have you received enough information about this study?	YES / NO
Do you understand that your are free to withdraw from this study <u>at any time</u> and <u>without giving a reason for withdrawing</u>?	YES / NO
Do you understand and accept the risks associated with the use of virtual reality equipment? Known risks are listed below:	YES / NO

- Using virtual systems, occasionally people experience some degree of nausea. You can stop and have a rest during the experiment at any time.
- There has been some research suggesting that people using virtual reality display might experience some disturbances in vision afterwards. No long term effects are known to us. Participants are advised not to drive a car, motorcycle, or use any machinery in the three hours immediately following being in virtual reality.

Do you agree to take part in this study? YES / NO

Please check:

I certify that I do not have epilepsy ☐

I certify that I will not be driving a car, motorcycle, bicycle, or use other types of complex machinery that could be a danger to myself or others, within 3 hours after the termination of the study ☐

Signed .. Date

Name in block letters .

Appendix II Pre-experiment questionnaire

Gender: ☐ Male ☐ Female **Age** *(optional)*: ____

Ethnicity: ☐ White ☐ Asian ☐ Black ☐ Oriental ☐ Arab ☐ Mixed Other: ____

Qualifications: ☐ GCSE ☐ Undergraduate ☐Postgraduate **Occupation**: ____

Please tick the appropriate answer to the following questions	Strongly Agree	Agree	Slightly Agree	Slightly Disagree	Disagree	Strongly Disagree
My "sense of direction" is very good.	☐	☐	☐	☐	☐	☐
My family/friends think that I have a good sense of direction.	☐	☐	☐	☐	☐	☐
When I'm in a complex building (many floors, stairs, corridors), I can indicate where the entrance is immediately.	☐	☐	☐	☐	☐	☐
I tend to think of my environment in terms of cardinal directions (North, South, East, West).	☐	☐	☐	☐	☐	☐
I am very good at giving directions.	☐	☐	☐	☐	☐	☐
I find my way best by remembering the routes connecting one place to another.	☐	☐	☐	☐	☐	☐
I find my way best by looking for recognisable features (landmarks, e.g. pub, petrol station).	☐	☐	☐	☐	☐	☐
I usually orientate myself by trying to create a map-like image of the area.	☐	☐	☐	☐	☐	☐
I like using maps.	☐	☐	☐	☐	☐	☐
I am very good at reading maps.	☐	☐	☐	☐	☐	☐
I am very good at judging distances.	☐	☐	☐	☐	☐	☐
I do not get lost very easily when visiting unfamiliar places.	☐	☐	☐	☐	☐	☐
I remember routes very well while riding as a passenger.	☐	☐	☐	☐	☐	☐
If I go to a new place, I easily know the way back.	☐	☐	☐	☐	☐	☐
I'm confident in finding my way when going to new places.	☐	☐	☐	☐	☐	☐
It is important to me to know where I am.	☐	☐	☐	☐	☐	☐
I like to explore unfamiliar places.	☐	☐	☐	☐	☐	☐

	Daily	2-3 times a week	Occasionally	Rarely	Never
How often do you use mobile phone?	☐	☐	☐	☐	☐
How often do you use palm computer?	☐	☐	☐	☐	☐
How often do you use text messaging?	☐	☐	☐	☐	☐
How often do you play electronic games?	☐	☐	☐	☐	☐

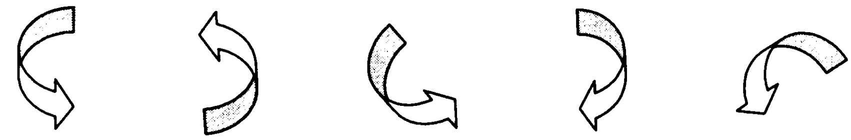
	Weekly	Monthly	2-5 times	Rarely	Never
How often in the last year have you used the Internet to find maps or travel instructions?	☐	☐	☐	☐	☐

	Computer Screen	Projected on wide-screen	Immersive VR Lab.	Other Lab.	Never
Have you had experience of virtual reality before?	☐	☐	☐	☐	☐

Do you drive a motorised vehicle? Rarely ☐ Occasionally ☐ Regularly ☐

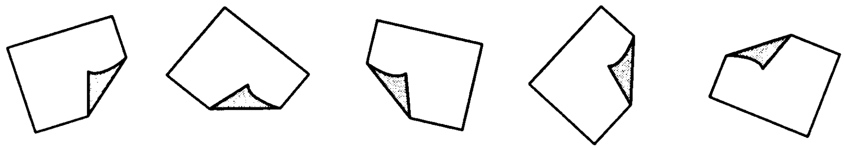
VISIO-SPATIAL ABILITY TEST

1. Find the odd **one** out:



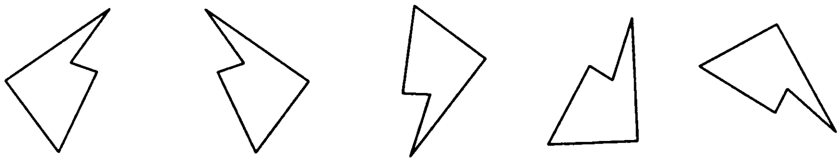
1 2 3 4 5 answer

2. Find the odd **one** out:



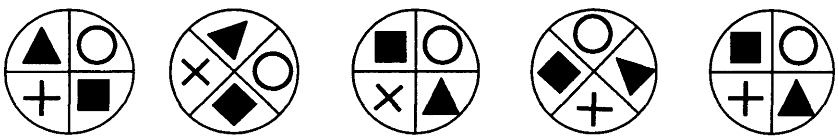
1 2 3 4 5 answer

3. Find the odd **two** out:



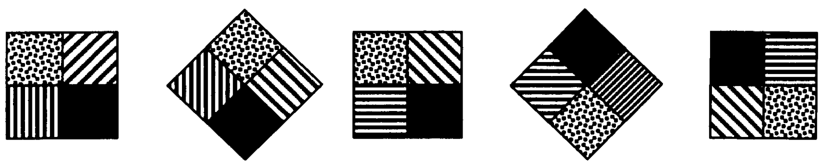
1 2 3 4 5 answer

4. Find the odd **one** out not in a pair:



1 2 3 4 5 answer

5. Find the odd **one** out not in a pair:

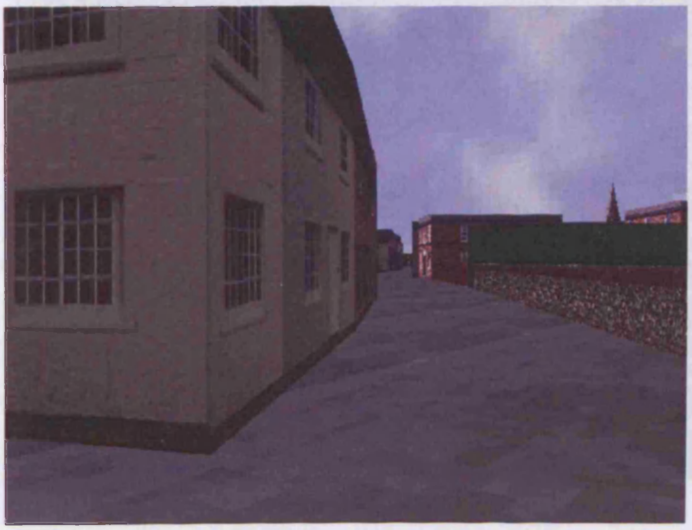


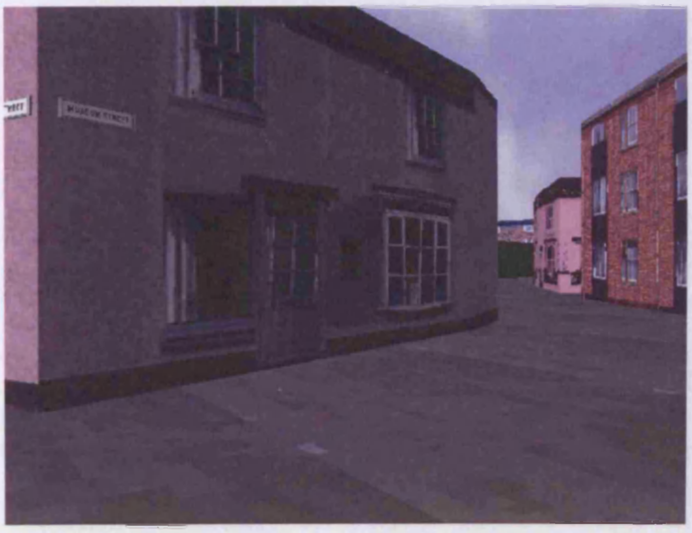
1 2 3 4 5 answer

Appendix III VR urban settings

Sample VR scenes of the areas in urban setting U1

Sample VR scenes of the areas in urban setting U2





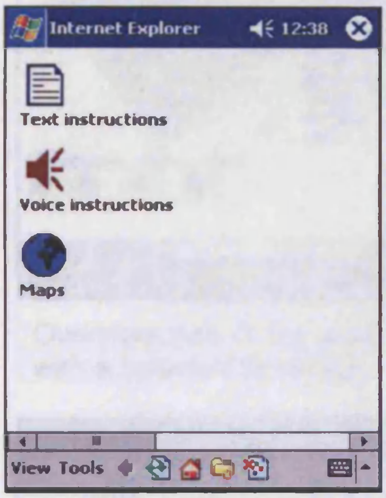

Cross Keys Hotel
Hotel

Urban setting U1: boundary road

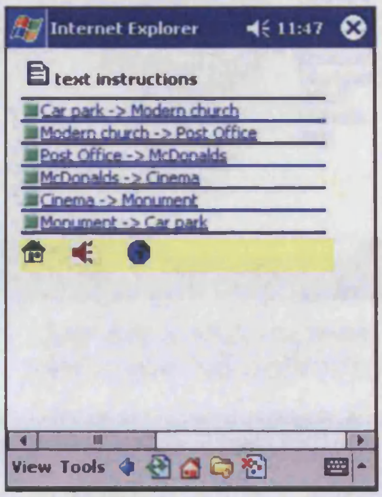
Urban setting U2: boundary road

Appendix IV Information provided on the PDA

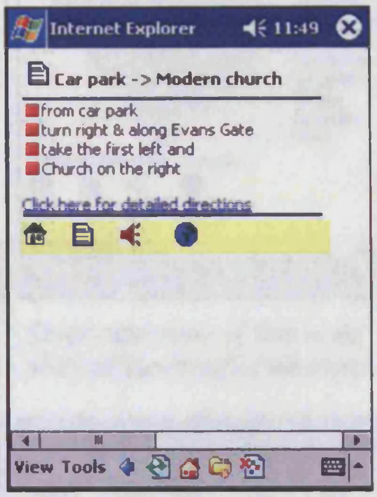
Sample PDA images for urban setting U1:



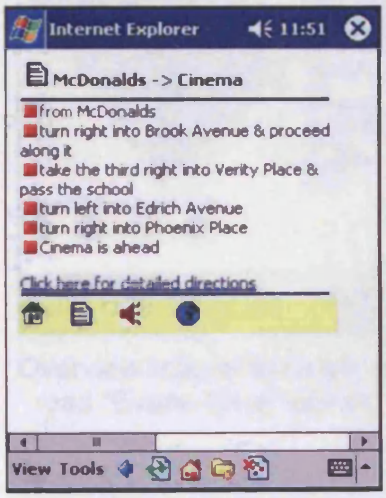
Content of table



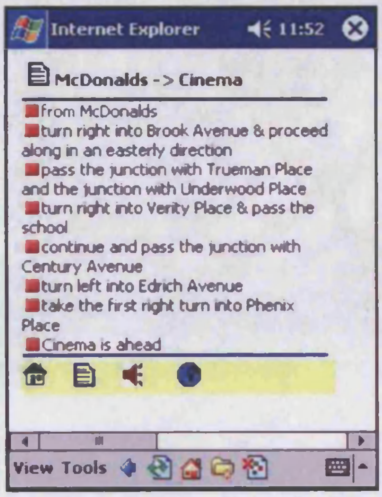
Text instruction list



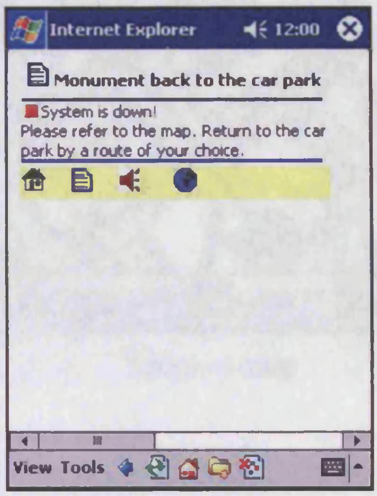
A sample of text instruction



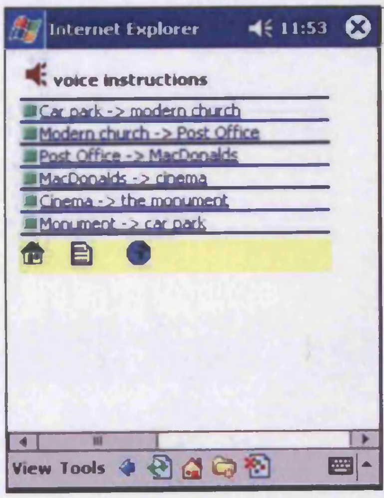
A sample of text instruction



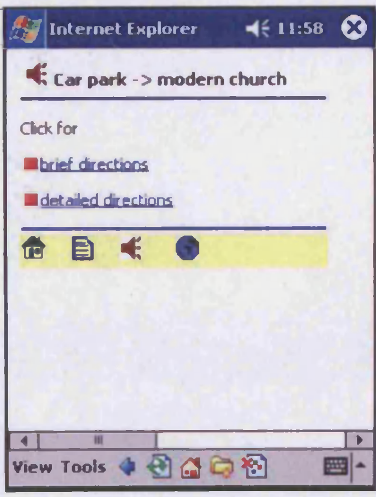
Detailed text instruction



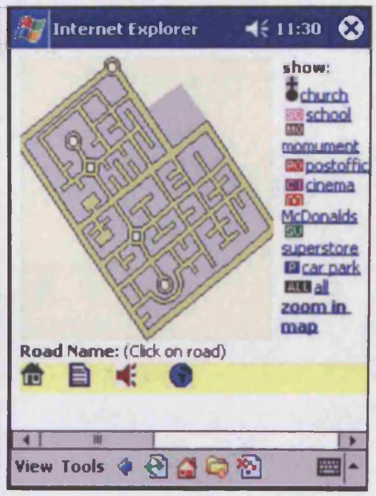
Text instruction for last leg



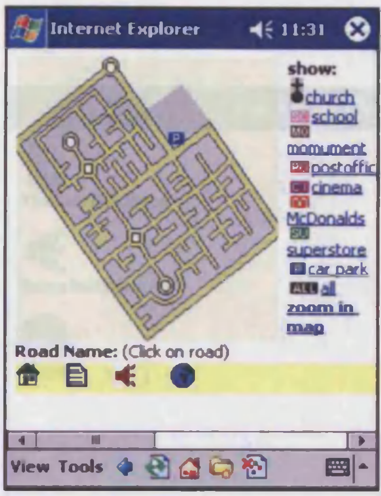
Voice instruction list



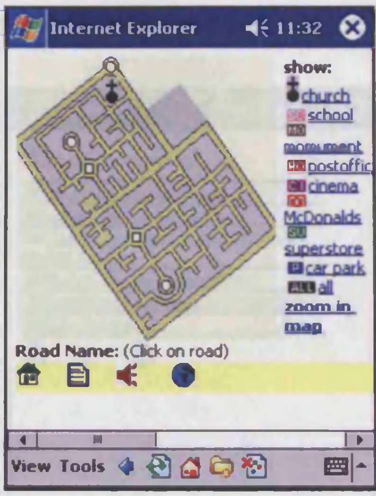
Voice instruction



Overview map of the area



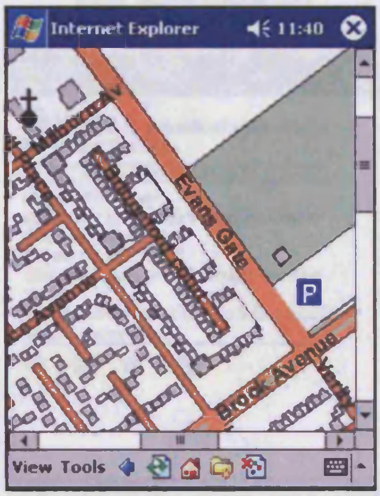
Overview map of the area with a selected landmark



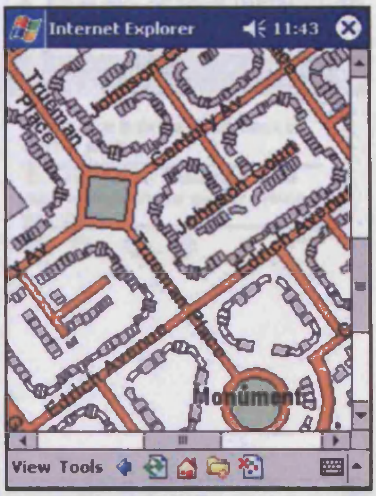
Overview map of the area with a selected landmark

Overview map of the area with all landmarks selected

Overview map of the area with road "Evans Gate" clicked

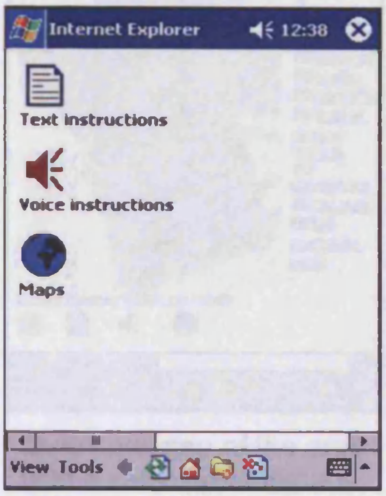


Zoom-in map

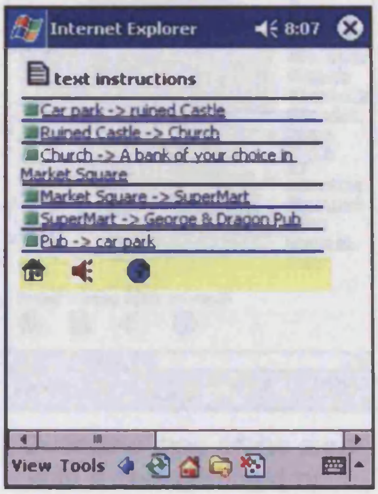


Zoom-in map

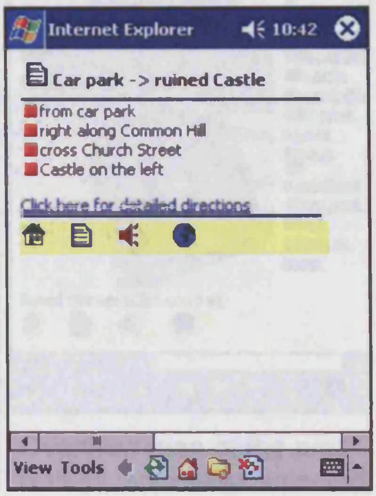
Sample PDA images for urban setting U2:



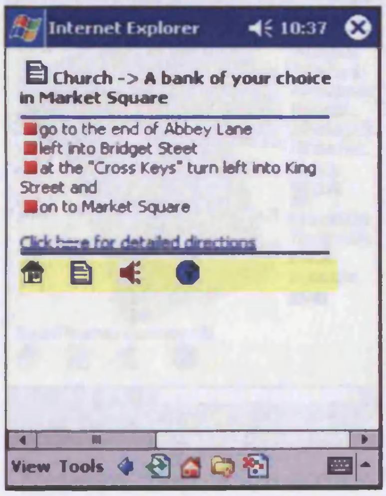
Content of table



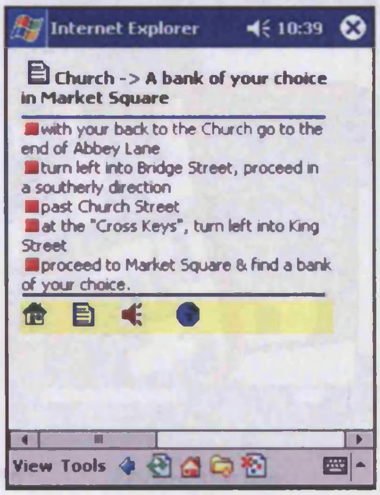
Text instruction list



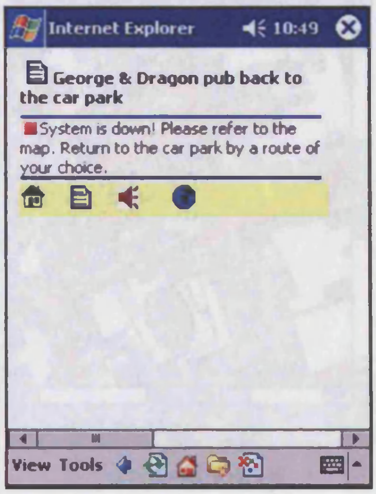
A sample of text instruction



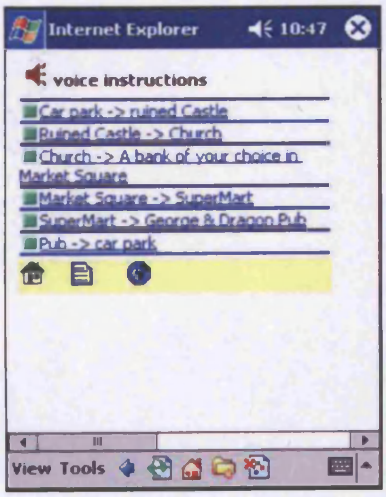
A sample of text instruction



Detailed text instruction

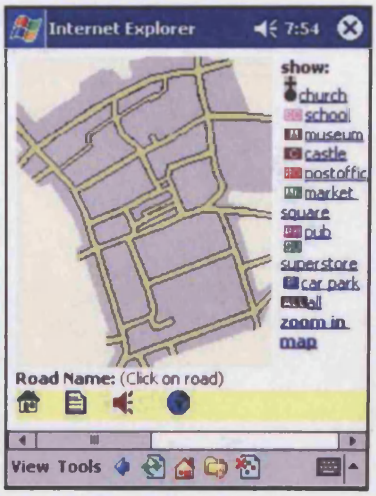


Text instruction for last leg

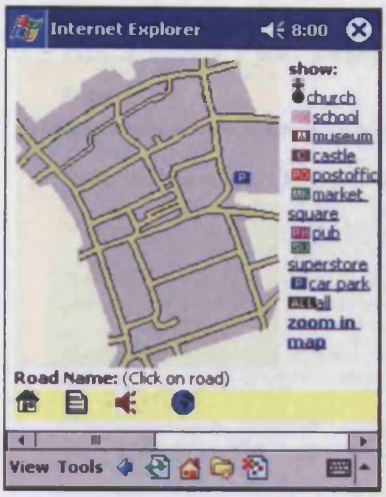


Voice instruction list

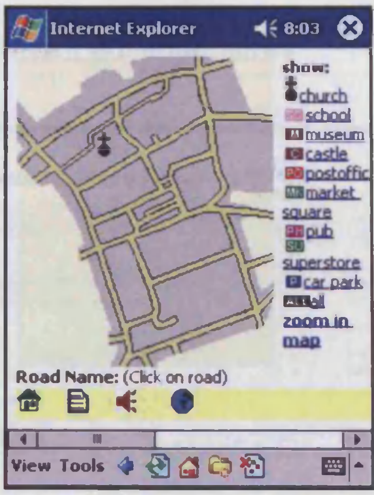
Voice instruction



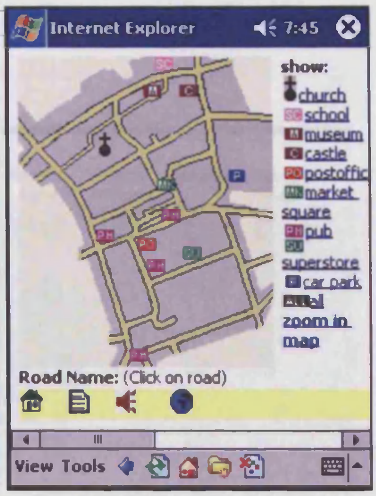
Overview map of the area



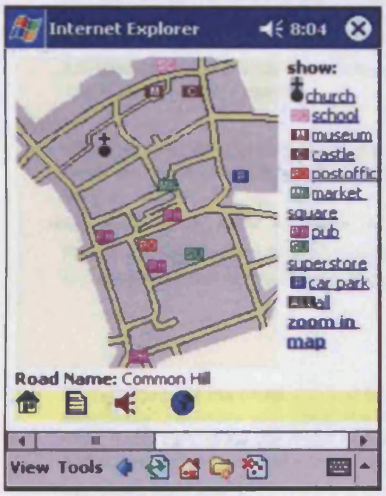
Overview map of the area with a selected landmark



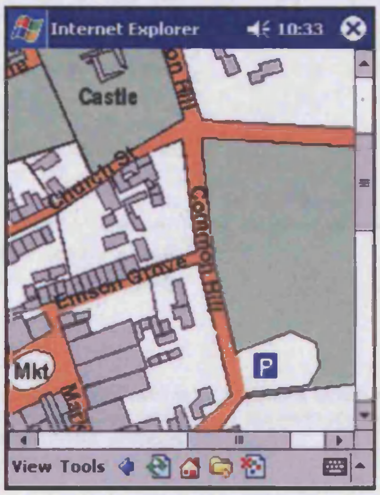
Overview map of the area with a selected landmark



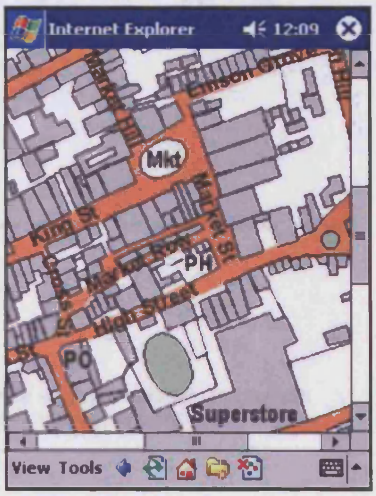
Overview map of the area with all landmarks selected



Overview map of the area with road "Common Hill" clicked



Zoom-in map



Zoom-in map

Appendix V Post-experiment questionnaires

Part 1

Please tick the appropriate answer to the following questions	Strongly Agree	Agree	Slightly Agree	Slightly Disagree	Disagree	Strongly Disagree
I had a sense of "being there" in the street.	☐	☐	☐	☐	☐	☐
During the experiment, the virtual town becomes the 'reality', and I almost forgot about the 'real world' of the laboratory.	☐	☐	☐	☐	☐	☐
For the virtual town I just experienced, it feels like I just visited somewhere instead of just looking at some images.	☐	☐	☐	☐	☐	☐
In terms of memory, I think of the virtual town I have just experienced in the same way I think of other places I have been to recently.	☐	☐	☐	☐	☐	☐
I find my way around in these virtual environments in a similar manner / approach as I do in the real world.	☐	☐	☐	☐	☐	☐
I do use similar features to find my way around in the real world as in these virtual environments.	☐	☐	☐	☐	☐	☐

Are there any specific factors which gave you a sense of 'really being' in the street?

Which specific factors pulled you out of 'really being' in the street and back to being just in a laboratory?

Please list any features you remembered about the place, and rank the most remembered as 1, 2, 3, ..., and so on.

Please describe the route you just took as an instruction to somebody unfamiliar with the place as much as you can. Also, if you can, draw the route with approximate distance and orientation of the features you remembered.

The route description:

Draw a sketch map with landmarks for the area with the route you taken (as best as you can):

Part 2

Please tick the appropriate answer to the following questions	Strongly Agree	Agree	Slightly Agree	Slightly Disagree	Disagree	Strongly Disagree
I find my way around in these virtual environments in a similar manner / approach as I do in the real world.	☐	☐	☐	☐	☐	☐
I do use similar features to find my way around in the real world as in these virtual environments.	☐	☐	☐	☐	☐	☐

Using the handheld device (e.g. PDA) on both experiments:

I find the map provided by PDA is helpful to find my way around?	☐	☐	☐	☐	☐	☐
I find the text provided by PDA is helpful to find my way around?	☐	☐	☐	☐	☐	☐
I find the voice provided by PDA is helpful to find my way around?	☐	☐	☐	☐	☐	☐

Rank the information sources in order of usefulness (1, 2, 3). Map ☐ Text ☐ Voice ☐

Did you find the PDA easy to use? Yes ☐ No ☐

If not, explain why.

What improvements should be made to the information currently presented on the PDA?

What additional information would also be useful on the PDA?

Please list any features you remembered about the place, and rank the most remembered as 1, 2, 3, ..., and so on.

Please describe the route you just took as an instruction to somebody unfamiliar with the place as much as you can. Also, if you can, draw the route with approximate distance and orientation of the features you remembered.

The route description:

Draw a sketch map with landmarks for the area with the route you taken (as best as you can):

Appendix VI Frequency of PDA information access for each route

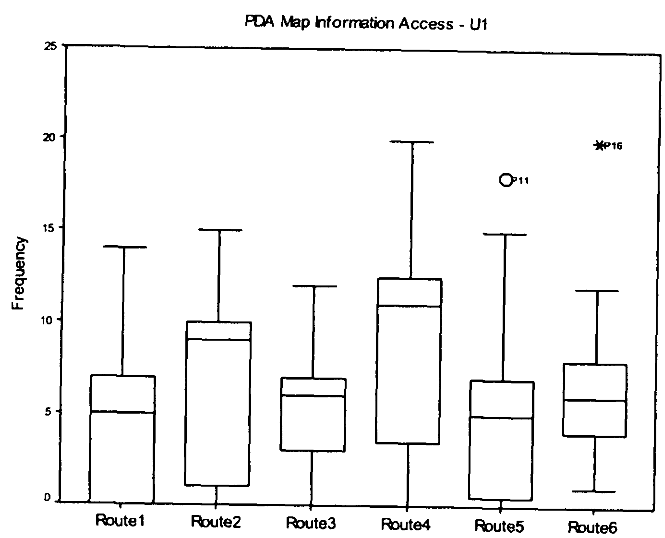
Frequency of PDA map information access in settings U1 and U2

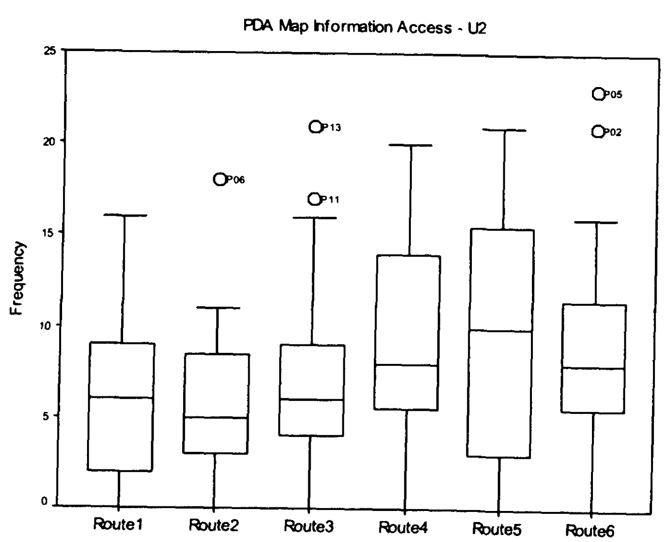
Statistical summary:

Urban Setting U1	Total	Route1	Route2	Route3	Route4	Route5	Route6
Mean	38.19	4.81	7.26	5.52	9.04	5.00	6.56
Std. Error of Mean	3.20	0.77	0.99	0.60	1.21	0.92	0.72
Median	41	5	9	6	11	5	6
Std. Deviation	16.62	4.02	5.16	3.12	6.28	4.80	3.77
Skewness	0.08	0.33	-0.37	0.26	-0.10	1.00	1.81
Kurtosis	-0.50	-0.54	-1.28	-0.30	-0.93	0.83	5.27

Urban Setting U2	Total	Route1	Route2	Route3	Route4	Route5	Route6
Mean	45.96	5.96	5.63	6.96	9.11	9.59	8.70
Std. Error of Mean	3.96	0.92	0.80	1.06	1.13	1.28	1.06
Median	48	6	5	6	8	10	8
Std. Deviation	20.57	4.76	4.17	5.50	5.85	6.67	5.52
Skewness	-0.38	0.38	0.80	0.76	0.16	0.04	0.91
Kurtosis	-0.67	-0.68	1.52	0.43	-0.92	-1.08	0.96

Boxplots:





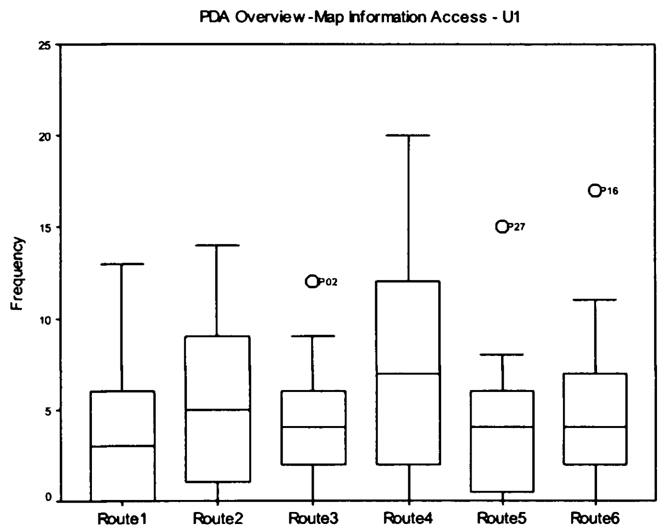
Frequency of PDA overview-map information access in settings U1 and U2

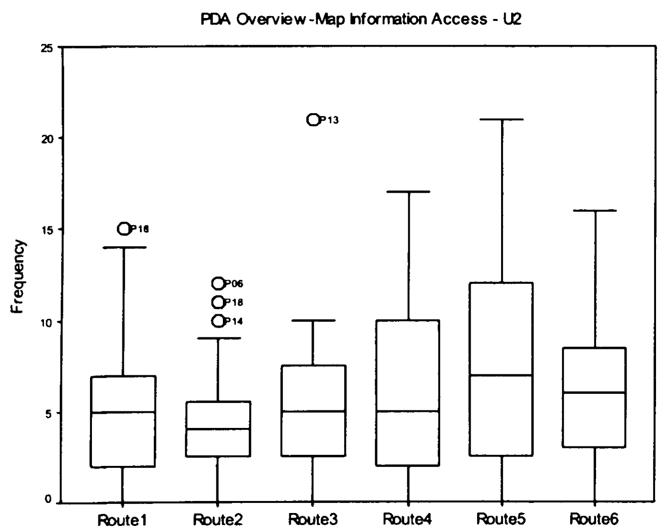
Statistical summary:

Urban Setting U1	Total	Route1	Route2	Route3	Route4	Route5	Route6
Mean	29.70	3.85	5.41	4.44	7.30	3.81	4.89
Std. Error of Mean	3.09	0.69	0.86	0.58	1.21	0.70	0.75
Median	28	3	5	4	7	4	4
Std. Deviation	16.05	3.58	4.47	3.00	6.26	3.62	3.90
Skewness	0.53	0.76	0.32	0.48	0.55	1.11	1.23
Kurtosis	-0.41	-0.03	-1.04	0.04	-0.60	1.85	2.28

Urban Setting U2	Total	Route1	Route2	Route3	Route4	Route5	Route6
Mean	35.48	5.11	4.44	5.33	6.52	7.81	6.26
Std. Error of Mean	3.68	0.82	0.68	0.86	1.04	1.14	0.77
Median	33	5	4	5	5	7	6
Std. Deviation	19.10	4.25	3.53	4.45	5.42	5.91	4.02
Skewness	0.32	0.68	0.62	1.47	0.67	0.47	0.66
Kurtosis	-0.40	0.03	-0.43	4.86	-0.68	-0.45	-0.01

Boxplots:





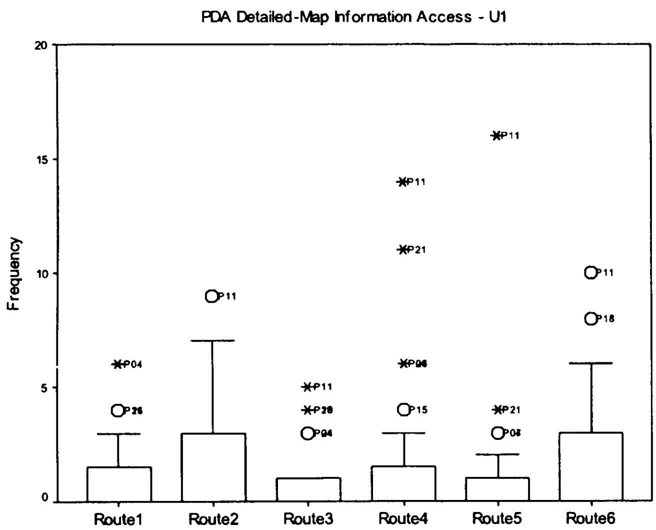
Frequency of PDA detailed map information access in settings U1 and U2

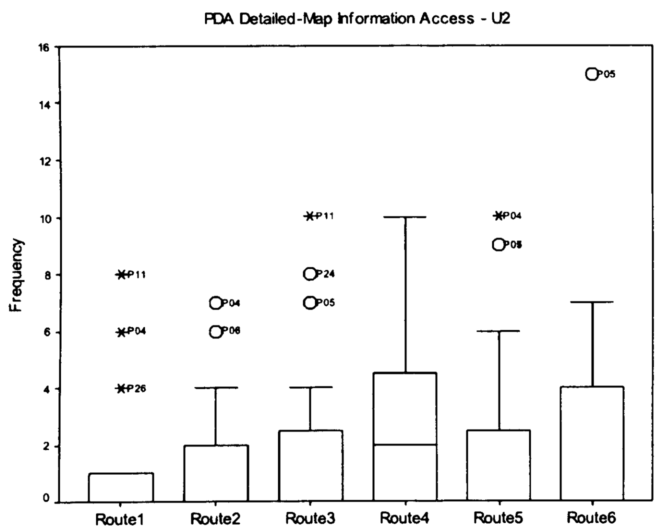
Statistical summary:

Urban Setting U1	Total	Route1	Route2	Route3	Route4	Route5	Route6
Mean	8.48	0.96	1.85	1.07	1.74	1.19	1.67
Std. Error of Mean	2.55	0.32	0.51	0.31	0.69	0.61	0.52
Median	3	0	0	0	0	0	0
Std. Deviation	13.23	1.65	2.63	1.59	3.60	3.19	2.69
Skewness	2.41	1.72	1.37	1.35	2.41	4.18	1.87
Kurtosis	6.80	2.25	0.89	0.43	5.49	19.31	3.08

Urban Setting U2	Total	Route1	Route2	Route3	Route4	Route5	Route6
Mean	10.48	0.85	1.19	1.63	2.59	1.78	2.44
Std. Error of Mean	2.32	0.38	0.37	0.53	0.59	0.59	0.67
Median	7	0	0	0	2	0	0
Std. Deviation	12.06	1.97	1.92	2.73	3.05	3.08	3.50
Skewness	1.24	2.81	1.86	1.93	0.97	1.85	1.99
Kurtosis	0.69	7.52	3.00	3.17	-0.12	2.27	5.16

Boxplots:





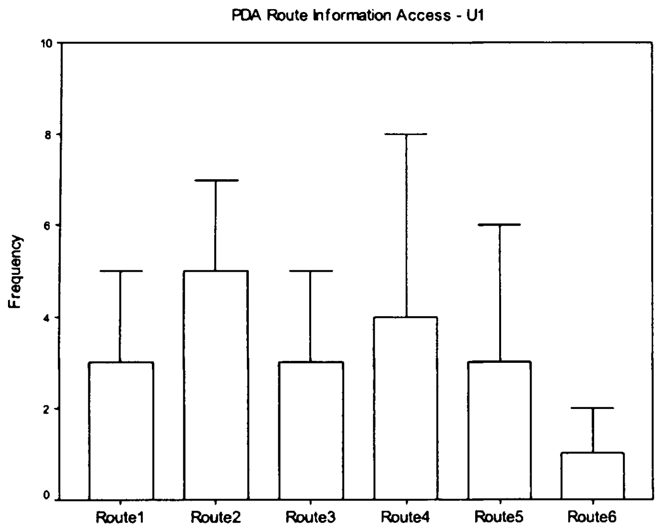
Frequency of PDA route information access in settings U1 and U2

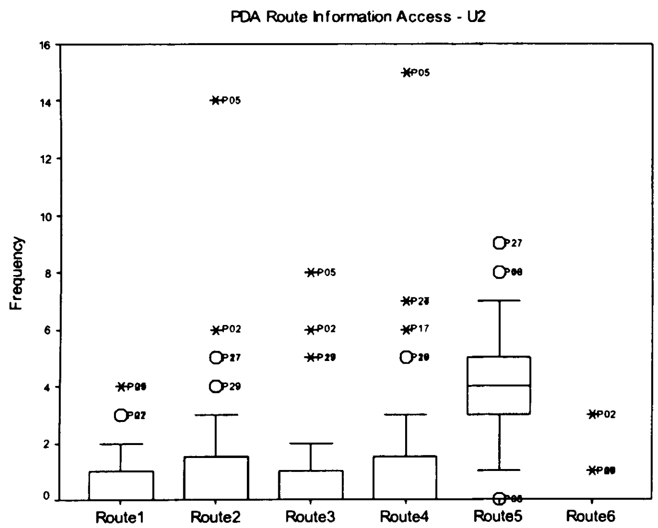
Statistical summary:

Urban Setting U1	**Total**	**Route1**	**Route2**	**Route3**	**Route4**	**Route5**	**Route6**
Mean	8.63	1.41	2.33	1.26	2.00	1.19	0.46
Std. Error of Mean	2.09	0.36	0.59	0.36	0.54	0.37	0.14
Median	1	0	0	0	0	0	0
Std. Deviation	10.88	1.87	3.09	1.87	2.83	1.94	0.71
Skewness	0.64	0.92	1.17	1.19	1.00	1.32	1.26
Kurtosis	-1.52	-0.71	0.63	0.14	-0.65	0.19	0.31

Urban Setting U2	**Total**	**Route1**	**Route2**	**Route3**	**Route4**	**Route5**	**Route6**
Mean	9.78	0.74	1.48	1.26	1.78	4.22	0.30
Std. Error of Mean	2.18	0.25	0.60	0.45	0.69	0.43	0.13
Median	5	0	0	0	0	4	0
Std. Deviation	11.32	1.32	3.12	2.31	3.58	2.26	0.67
Skewness	1.96	1.61	2.88	1.79	2.39	0.18	2.91
Kurtosis	3.88	1.25	9.66	2.04	6.33	-0.20	9.90

Boxplots:





Appendix VII Time spent on PDA information usage for each route

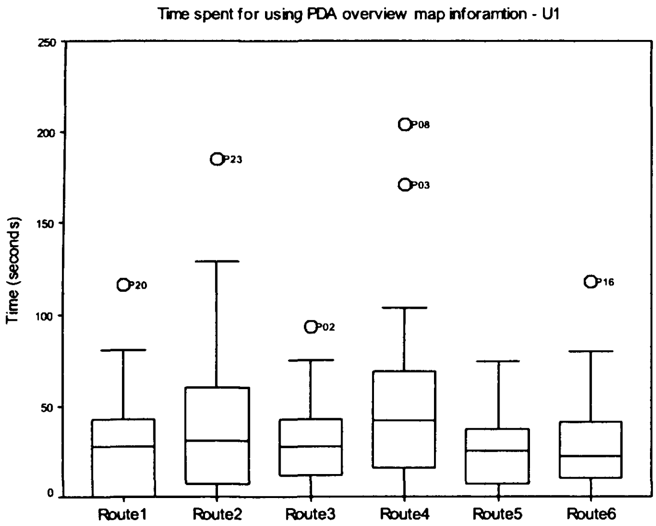
Time spent for using PDA overview map information in settings U1 and U2

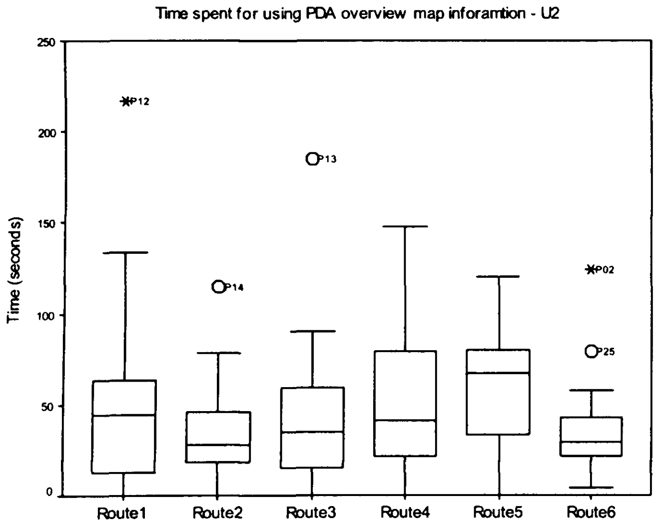
Statistical summary:

Urban Setting U1	Total	Route1	Route2	Route3	Route4	Route5	Route6
Mean	210.63	30.52	43.67	31.48	49.26	26.48	29.22
Std. Error of Mean	21.92	5.62	8.82	4.91	9.53	4.23	5.42
Median	215	28	31	28	42	25	22
Std. Deviation	113.92	29.21	45.84	25.49	49.50	21.99	28.18
Skewness	0.39	1.07	1.47	0.78	1.69	0.59	1.50
Kurtosis	-0.64	1.36	2.26	-0.08	3.43	-0.16	2.49

Urban Setting U2	Total	Route1	Route2	Route3	Route4	Route5	Route6
Mean	268.48	48.78	33.93	40.74	52.04	58.30	34.70
Std. Error of Mean	24.47	9.70	5.24	7.62	8.13	6.80	4.85
Median	254	44	28	35	41	67	29
Std. Deviation	127.16	50.41	27.21	39.60	42.24	35.31	25.21
Skewness	0.09	1.68	1.15	1.93	0.81	-0.32	1.92
Kurtosis	-0.55	3.64	1.67	5.73	-0.20	-0.83	5.13

Boxplots:



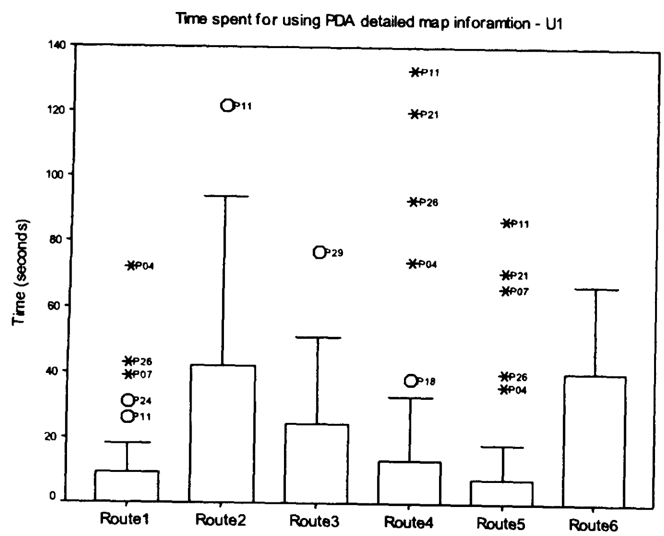


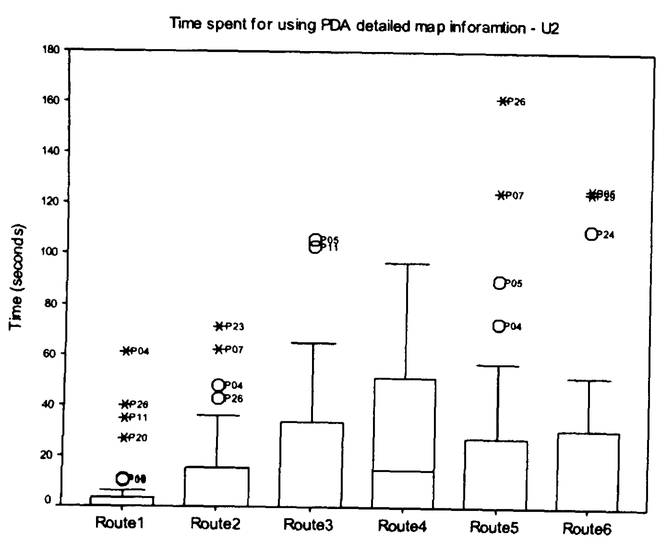
Time spent for using detailed PDA map information in settings U1 and U2

Statistical summary:

Urban Setting U1	Total	Route1	Route2	Route3	Route4	Route5	Route6
Mean	96.37	9.30	24.56	13.48	19.19	12.33	17.52
Std. Error of Mean	25.37	3.46	6.83	3.95	7.47	4.82	4.88
Median	38	0	0	0	0	0	0
Std. Deviation	131.81	17.99	35.50	20.55	38.82	25.04	25.34
Skewness	1.57	2.23	1.42	1.61	2.09	2.04	1.00
Kurtosis	1.70	4.94	1.06	2.17	3.29	3.10	-0.78
Urban Setting U2	Total	Route1	Route2	Route3	Route4	Route5	Route6
Mean	113.52	7.07	12.41	18.74	27.30	23.89	24.11
Std. Error of Mean	24.58	2.97	4.05	5.89	5.99	8.17	7.33
Median	66	0	0	0	15	0	0
Std. Deviation	127.70	15.42	21.04	30.60	31.13	42.46	38.08
Skewness	1.19	2.44	1.70	1.86	0.72	2.11	1.92
Kurtosis	0.50	5.58	1.83	3.00	-0.82	4.08	2.88

Boxplots:





Time spent for using PDA route information in settings U1 and U2

Statistical summary:

Urban Setting U1	**Total**	**Route1**	**Route2**	**Route3**	**Route4**	**Route5**	**Route6**
Mean	59.89	9.00	15.59	8.48	10.19	11.41	5.22
Std. Error of Mean	14.84	2.64	4.72	2.92	3.42	3.62	1.69
Median	0	0	0	0	0	0	0
Std. Deviation	77.09	13.74	24.50	15.20	17.76	18.83	8.78
Skewness	0.85	1.78	1.78	1.66	1.45	1.71	1.77
Kurtosis	-0.80	2.76	2.93	1.50	0.52	2.08	2.71
Urban Setting U2	**Total**	**Route1**	**Route2**	**Route3**	**Route4**	**Route5**	**Route6**
Mean	105.48	4.81	11.70	14.22	18.37	52.26	4.11
Std. Error of Mean	21.96	1.60	4.26	6.73	8.80	7.32	2.06
Median	65	0	0	0	0	48	0
Std. Deviation	114.13	8.29	22.14	34.98	45.74	38.05	10.69
Skewness	2.11	1.49	2.06	4.17	3.28	2.61	3.10
Kurtosis	5.15	0.87	3.71	19.39	11.71	9.99	9.80

Boxplots: